Bachelor thesis

World Baseload Energy Production: Fossil Fuels Reserves and Nuclear Energy potential

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Acknowledgements

Firstly, I wish to express my sincere thanks to my mentor, Victor Tribaldos, for his guide, sympathy and all the dedication and care that made this project possible. This work would have never existed without him.

I will also like to thank my family for all the support they provided me and my friends for continuously encouraging me during the realization of this project.

Abstract

This project focuses in analysing the baseload energy production at a global level. Fossil fuels and nuclear energy are the only two developed technologies capable to produce this type of energy (constant and big quantities) and are the ones that will be studied in this work.

Firstly, a brief description of the actual worldwide energetic situation will be performed to supply a basic idea of the situation of the energetic sector, providing a context for the following analysis. Then, we will proceed to calculate the energy stored in the earth during all its history in form of fossil fuels, to do so the energy provided by the sun to the earth will be calculated and all the other factors affecting the conversion from sun energy to fossil fuel will be taken into account, obtaining an estimation of the fossil fuels reserves.

Furthermore, a brief description of nuclear fission energy will be implemented before analysing the possible substitution of fossil fuels energy by nuclear calculating providing objective data about the rentability of this change, time necessary, cost, , premature deaths avoided etc.

Finally, the fusion energy will be explained briefly to give some basic knowledge about its advantages and the actual state of development of this type of energy.

Abstracto

Este proyecto se centra en analizar la producción de energía base a nivel global. Los combustibles fósiles y la energía nuclear son las dos únicas energías completamente desarrolladas capaces de producir este tipo de energía (grandes cantidades de manera constante) y son las que serán analizadas en este trabajo.

En primer lugar, se realizará una breve descripción de la situación energética actual para poner en contexto los análisis que se realizaran más adelante. Entonces, se procederá a calcular la energía almacenada en la tierra durante toda su historia en forma de combustibles fósiles, para ello se calculará la energía que recibe la tierra del sol y todos los otros factores que interactúan con el proceso de creación de los combustibles fósiles

a partir de la energía del sol, obteniendo una estimación de las reservas de combustibles fósiles.

Además, se realizará una breve descripción de la energía de fisión para posteriormente analizar una posible sustitución de la energía de los combustibles fósiles por ella obteniendo resultados como rentabilidad tiempo coste muertes evitadas, etc.

Finalmente se realizará una breve explicación sobre la energía de fusión y el estado actual en su desarrollo, así como sus ventajas.

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Chapter 1: Introduction

Energy production is the force that drives human´s developing since the most basic way of producing heat was discovered, the fire. The human history can be shown as a cycle of discovering of new ways of producing energy, normally, by the introduction of a new resource with latent energy in it and the discovery of a way to transform this energy into something useful for the human beings. These cycles are based in three phases; discovering, applications and scarcity of resource. During the first two phases of the cycle, the society increases exponentially the quality of life by using this energy until it becomes a necessity for the daily life. Once the resource has been exploited until the quantities of it accessible with the available technology begin to decrease, the third phase of the cycle begins, scarcity. Scarcity of an element that has become a primary necessity leads to conflict between the nations which are trying to provide this resource to their inhabitants, this conflict can be shown in several ways, in the worst case as war. The conflict continues until a new upcoming source of energy or a combination of sources reaches the level of demand of the society, but in every passing cycle the necessity level is increasing until the energetic demand we have nowadays making more and more difficult to avoid a situation where the scarcity of a resource is solved by a new one. In actuality we are approaching a scarcity phase for the fossil fuels that have been the base for our energy mix the las centuries.

New different ways of producing energy have surged in the last year to try to substitute fossil fuels and avoid this problem, recently the ones receiving more attention and investigation effort are renewables. This type of technology is able to produce energy without emissions from infinite sources such as sun and wind at low costs. However, renewables are still developing and its low efficiency and energy density makes necessary huge amounts of land to produce relevant energy loads. In addition, the biggest constraint of renewables is the intermittence in their production, completely dependent in climatological conditions, which transform them into an unreliable source of energy until energy storage suffers a huge development. The previously exposed factors show that renewables are not fit to produce the baseload energy for the global energy mix, at least not yet, making necessary the implementation of a new source of energy.

The nuclear energy appears as the only already developed technology capable of fulfilling the same functions than fossil fuels while producing 0 emissions and depending on an almost unexploited source, uranium. Nevertheless, nuclear energy supposes a serious hazard potential and the waste management which need a careful and expensive treatment is a relevant technical difficulty. Further the use of this type of energy is very controversial and the public opinion is positioned clearly against it.

In this work the substitution of fossil fuels by nuclear energy will be analyzed providing objective information in both benefits and drawbacks in the implementation of this energy source. The analysis will be performed taking into account the economic and the society effects this change will produce and will try to provide a final conclusion about the viability of this substitution.

1.1 Road map

Chapter 2 “World energetic situation” aims to provide a general idea about the energy necessities of the actual world and how the energy is produced to achieve this level of demand analyzing two different blocks; fossil fuels and non-fossil fuels.

Chapter 3 “Fossil fuels reserves calculation” will firstly calculate all the fossil fuels used during all the history. Then the sun energy reaching the earths will be used to estimate the energy stored in the earth in form of fossil fuels knowing the eras where they were created. Once both things are calculated an approximation of the actual fossil fuels reserves will be performed.

Chapter 4 “Fossil fuels substitution by nuclear fission” will explain the basic principles of fission energy as well as its benefits and drawbacks followed by an exhaustive analysis of the substitution of the fossil fuels by fission energy that will provide numerical results of all the factors affected by this change providing an economic conclusion about the substitution of each individual fuel. In addition brief explanation on regulations applied to the construction of new nuclear power plants will be presented.

Chapter 5 “Nuclear fusion” aims to briefly explain the fusion energy showing all its potential as future energy source and provide an update in the actual state of development of this type of energy production.

Chapter 2: World Energetic situation

This project is going to refer to the data of 2015 as it is the last year where the IEA has made a complete energy outlook [1] due to the high complexity of collecting the data worldwide. In order to provide more detailed information, the EIA international outlook [2] and the bp energy outlook of 2018 [3] will also be taken as reference.

As this work is going to be centered in the resources used and the possible substitution of the sources of energy the data necessary to create the context is the production instead of the demand, the production values will be higher than the demand ones as the energy is primary necessity for our society and the energy availability must be assured.

As the society demand for energy grows every year so does the production, from 2014 to 2015 the world energy production has suffered an increase of 0,6% reaching 13790 Mega tonnes of oil equivalent (Mtoe).

Fossil fuels:

The 81,7% of the world energy comes from fossil fuels which suppose a reduction compared to the 81,9% of 2014 mainly caused by the huge coal reduction.

Among the fossil fuels the oil production increased 2,3% in 2015, generating 33,4% of the total world energy and the preliminary data shows that in 2016 oil increase will be highly reduced to a slight increase of 0,1%. It is still increasing but at a much slower rate, however the data is preliminary and a single year is not a sample large enough to consider as a trend the reduction in the increase rate of oil production.

Natural gas production increased 1,4% in 2015 reaching the 22,3% of total energy production the 2016 preliminary data shows that the gas production increase is reduced to 0,7% exactly half of 2014.

Coal production differs from the other fossil fuels as it is decreasing instead of increasing. Coal production suffered a reduction of 2,6 %, being the first reduction suffered by this type of energy production since 1999, meaning the 26% of total energy produced. Still a higher value than natural gas but in 2016 provisional data shows that coal suffers an even greater decrease of 4,5%. The coal usage fall is caused by the OECD countries (-95 Mtoe) and China (-110 Mtoe) two of the main agents capable of producing changes in the world energy mix, specially China.

In general, it can be observed that the data shows the beginning of a decrease in the fossil fuels utilization specially coal.

Non- fossil fuels:

Non-fossil fuels suffer an increase proportional to the fossil fuels reduction reaching a production of 18,3%, a very low amount compared to the previous one, however the non-fossil fuels group is increasing at a rising rate leaded specially by renewables.

Biofuels production share remains almost constant being 9,6% in 2015 0,1% more than in 2014.

Hydro produces 2,4% of total world energy production, exactly the same as in 2014.

The other renewables are increasing rapidly but still accounts only 1,4% of total production. Nevertheless, the increase pace is encouraging, wind energy increased 16,8%, solar thermal 6,8%, solar PV 29,7% and geothermal 4,1%.

Nuclear energy increased its share by 1,4% in 2015, reaching a production of 4,9%.

Overview:

Energy source	% change 2014-2015	% World Share	Production (Mtoe)	% change 2015-2016
Total	+0,6	100	13790	Unknown
Fossil fuels	-0,2	81,7	11260	-1,3
Oil	+2,3	33,4	4620	+0,1
Natural Gas	+1,4	22,3	3120	+0,7
Coal	-2,6	26	3620	-4,5
Non-fossil fuels	+0,2	18,3	2530	Unknown
Biofuels	+0,1	9,6	1330	Unknown
Hydro	+0	2,4	330	Unknown
Other renewables	Wind +16,8 Solarthermal+6,8 SolarPV +29,7 Geothermal +4,1	1,4	190	Unknown
Nuclear	+1,4	4,9	675	Unknown

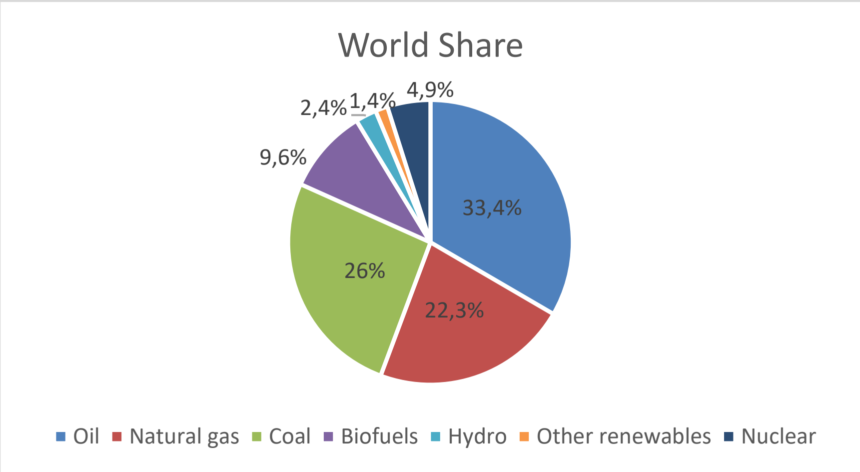

Figure 1: Overview World energetic situation. Souce: IEA, own development

Chapter 3: World Fossil fuels reserves calculation

The Chapter 2 showed the high dependency on fossil fuels that our society suffers, they produce 81,7% of the world energy. In order to produce this energy huge amounts of oil gas and coal are needed, these resources are not generated but extracted from the earth as they are generated naturally when some geological and ambient conditions are fulfilled, being the earth 4,543 thousand million years old large reserves of fossil fuels have been created. Nevertheless, the process of creation of fossil fuels is extremely slow, the process last millions of years, especially compared with the rate of human consumption.

The amount left of fossil fuels reserves is very complicated to estimate as a lot of them are yet to be discovered and the rate of discoveries is treated as classified information by the enterprises in charge of its exploit. It is also necessary to note that some of the deposits may not be accessible by the actual technology for example very depth in the sea or extremely expensive to exploit making the resource usage unprofitable, at least with actual prices.

This work will calculate an approximated quantity of the fossil fuels generated during the earth history by calculating the sun´s energy accumulated in the plants during the periods where the fossil fuels where created.

3.1 Fossil fuels used during history

To estimate the remaining reserves of fossil fuels it is necessary to know the quantity of them already used.

The first fossil fuel to be used in a relevant size is the coal; it started during the industrialization in the XVIII century specially in Europe and America while the gas and oil usage started much later around the 1800´s.

In the beginning of the fossil fuels usage there was not a great concern about the precedence of the resources and the possibility of its scarcity so no measurements about the size used were made making impossible the access to direct data. However, the amount of CO_2 emitted during these years is available and it is possible to define the source of these emissions as each of the different fossil fuels usage is accompanied by specific emissions [4] so the amount of CO_2 generated by each fossil fuel can be calculated.

3.1.1 Coal

There exist 4 different types of coal each one with its own emission factor and energy density, the types are lignite, sub-bitominous coal, bitominous coal and anthracite representing the 17%, 30%, 52% and 1% or world reserves respectively. As the most common one and the most used for energy generating process is the bitominous coal we will use this type of coal as reference for all the calculations. So, the calculations will be performed with an energy density of 8,1111$\frac{KWh}{Kg\ coal}$ [5]and an emission factor of 0,34056 $\frac{KG\ CO_2}{KWh}$ [6]. Once the data is stablished the equation 1 will be used to calculate the kg of coal consumed per kg of $CO_{2_{Coal}}$.

$$kg\ of\ fossil\ fuel\ per\ kg\ of\ \mathrm{CO}_2 = 1kg\ \mathrm{CO}_2 * \frac{1}{EF} * \frac{1}{ED} \quad (1)$$

$$kg\ coal\ per\ kg\ \ CO_{2_{Coal}} = 1kgCO_{2_{Coal}} * \frac{1\ KWh}{0{,}34056\ kg\ CO_{2_{Coal}}} * \frac{1kg\ Coal}{8{,}1111KWh} \quad (2)$$

The result shows that 0,362015 kg of coal are consumed per every kg of $CO_{2_{Coal}}$, and applying this conversion factor to the CO_2 data during history we obtain an approximation of the total coal consumed during history showed in figure 2:

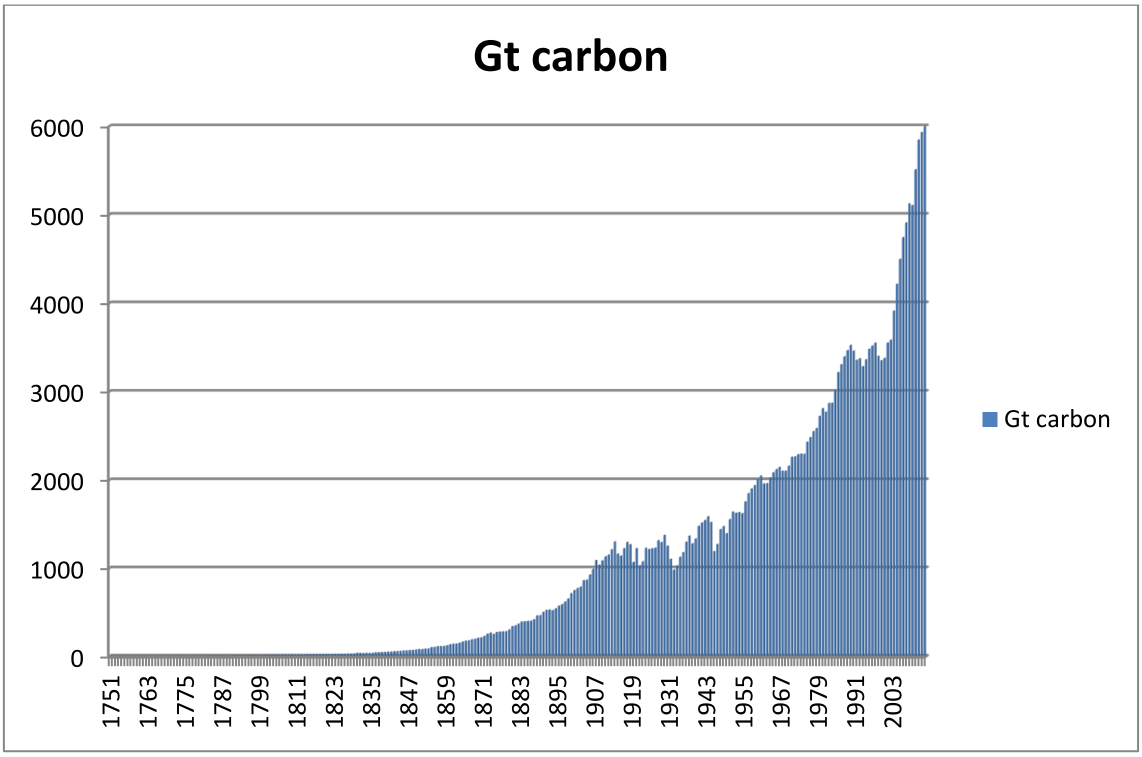

Figure 2: Coal used during history. Source: own development

The total amount of coal consumed is 258 Tt that in terms of energy reaches 2095 PWh or 7542 EJ.

3.1.2 Oil

In the oil case the Crude oil properties will be used in the calculations being the energy density 12,5 $\frac{KWh}{kg\ Oil}$ [5] and the emission factor 0,26387 $\frac{KG\ CO_2}{KWh}$. Applying the equation (1) to the oil case we obtain that 0,303179596 kg of oil are consumed per kg of $CO_{2_{Oil}}$. Utilizing this transformation to the $CO_{2_{Oil}}$ data the following results are obtained showed in the figure 3:

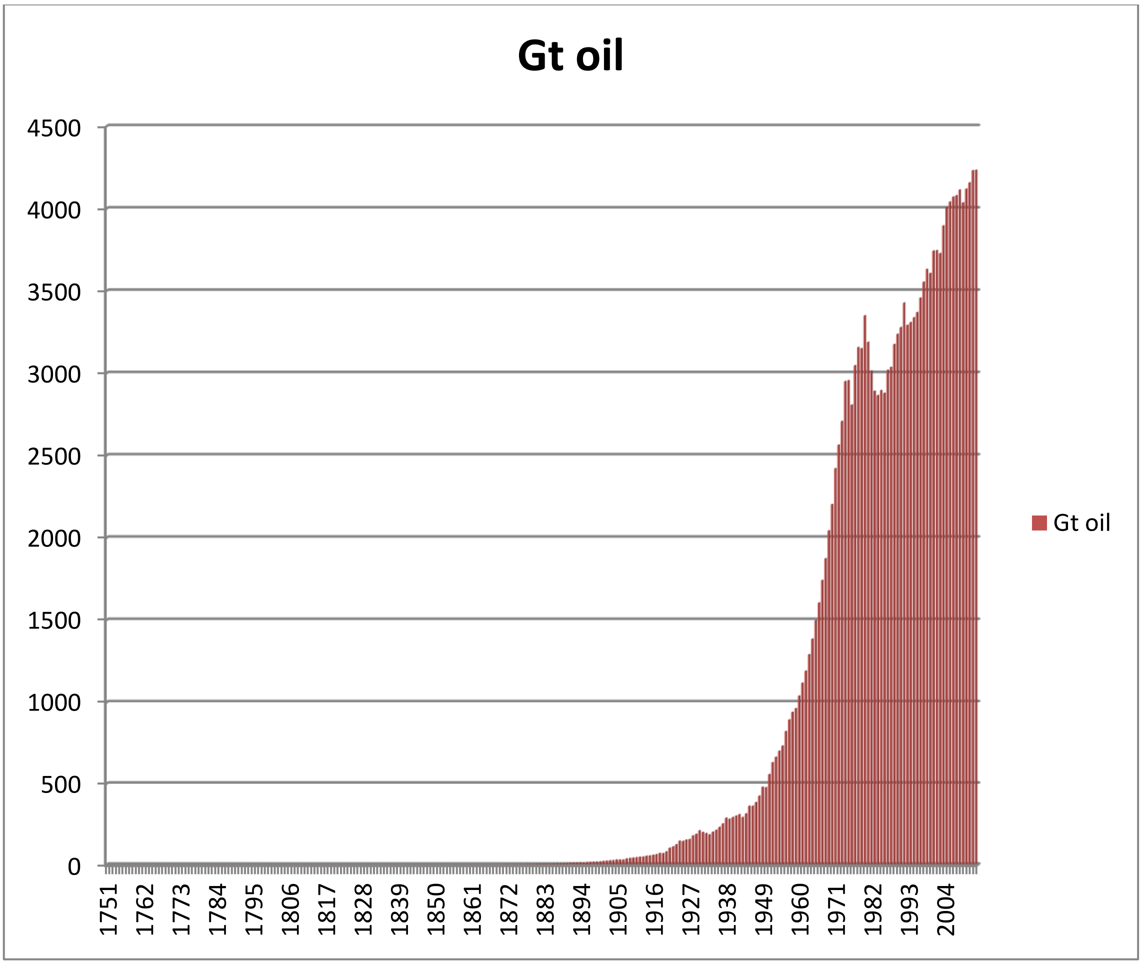

Figure 3: Oil used during history. Source: own development

As can be observed from the table the use of oil started much later than the coal one but while the coal usage increased during a lot of years at a moderate speed the oil usage increased at an incredible rate making itself necessary in about 30 years due to its high energy density 12,5 $\frac{KWh}{kg\ Oil}$ compared to the coal 8,1111$\frac{KWh}{Kg\ coal}$.

The total amount of Oil consumed is 161 Tt and the amount of energy generated by oil is 2015 PWh or 7254 EJ.

3.1.3 Natural gas

In this final case the properties of natural gas are going to be used being its energy density 13,56944 $\frac{KWh}{Nm^3}$ and the gas CO_2 emission factor 0,23111 $\frac{KG\ \mathrm{CO_2}}{KWh}$. The equation (1) is applied for the last time with the gas specifications obtaining that per each kg of ${CO_2}_{Gas}$ 0,3188742 Nm^3 of gas are depleted. Implementing the precedent result to the ${CO_2}_{Gas}$ data we obtain the results showed in figure 4:

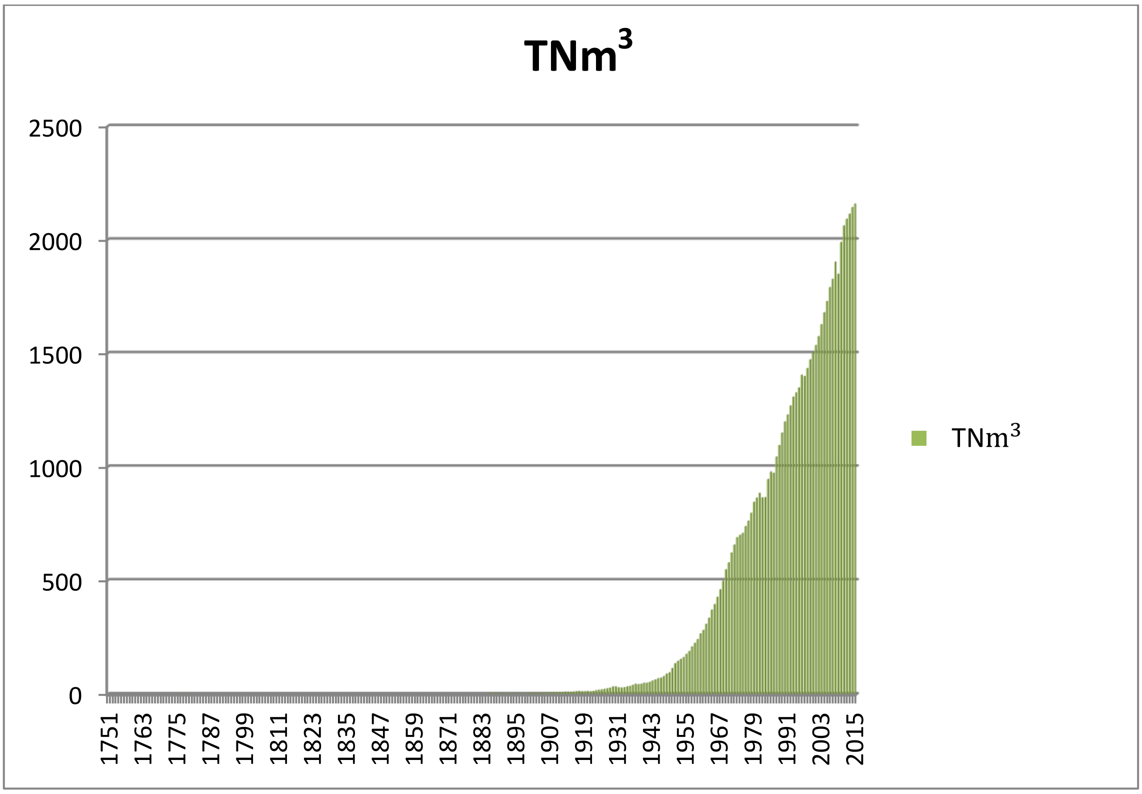

Figure 4: Natural gas used during history. Source: own development

As can be observed the gas is less used than the other two fossil fuels even with a higher energy density and less CO_2 emissions, mainly caused by the difficulty to find gas reserves compared to coal and oil´s ones.

The amount of gas spent during history is 67 PNm^3 and the amount of energy produced by gas is 905 PWh or 3258 EJ.

3.1.4 Comparison between fuels

The fossil fuel predominant during history is clearly the coal as the figure 5 shows, however the coal reached shares of about 100% energy generation during the first years where the energy started to be used in the industry and transport, the situation has evolved to a scenario where the fuels usage is much more balanced. It is also interesting to note how fast the introduction of oil was reaching very high rates of consumption in very few years.

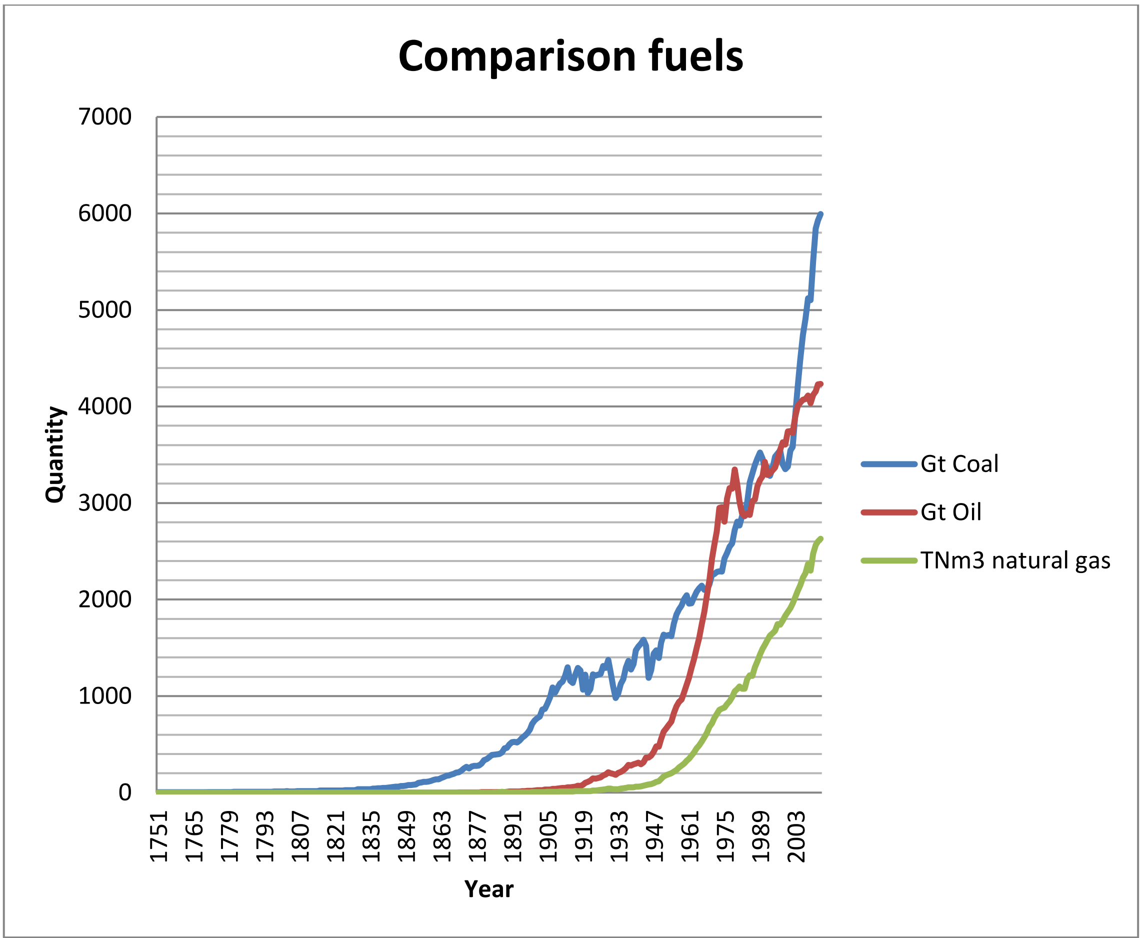

Figure 5: Comparison fossil fuels used during history. Source: own development

3.2 Energy received by earth from sun

To make an approximation of the energy stored in the earth in form of different potential energies it is necessary to calculate the sun´s energy that the earth receives.

3.2.1 Solar irradiance during a year

The sun approximately emits an average irradiance $I_{Solar\ constant}$ of 1,367 $\frac{KW}{m^2}$ received by a plane perpendicular to the earth [7]. As the earth orbits around the sun in an ellipsis the distance between the two varies along one orbit (365,25 days). In an elliptical movement the sun is not located in the center of the orbit and talking in cosmic scale the distance is depreciable but will be taken into account in this work. Two points are specially interesting to analyze; the Perihelion (2-4 of January) is the closest distance between sun and the earth and the Aphelion (4-6 of July) is the largest one, figure 7 shows the location of these two points. The difference between these two points has slight variations depending on the year but on average is around 5 million km [8].

However, the irradiance difference on a perpendicular plane to the sun (I_O) caused by the distance variance can be calculated using the equation:

$$I_O = I_{Solar\ constant} * \left[1 + 0{,}034 * \cos\left(2 * pi * \frac{n}{265{,}25}\right)\right] \quad (3)$$

n is the day of the year being the first of January n=1

Applying equation 3 during a whole year the figure 6 is obtained:

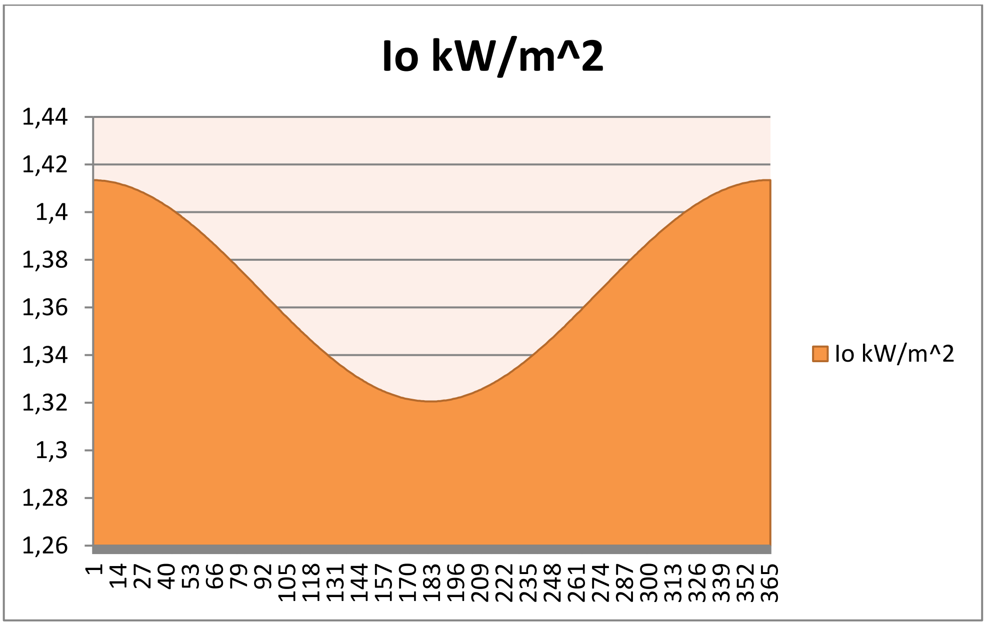

Figure 6: Irradiance along year. Source: own development

3.4.2 Solar declination angle

The point perpendicular to the sun plane(P) is not constant, it changes during the year and the Earth´s position along the orbit as the figure 7 shows. This effect is a consequence of the tilt in earth´s axis, exactly a tilt of 23,45º with respect to the ecliptic.

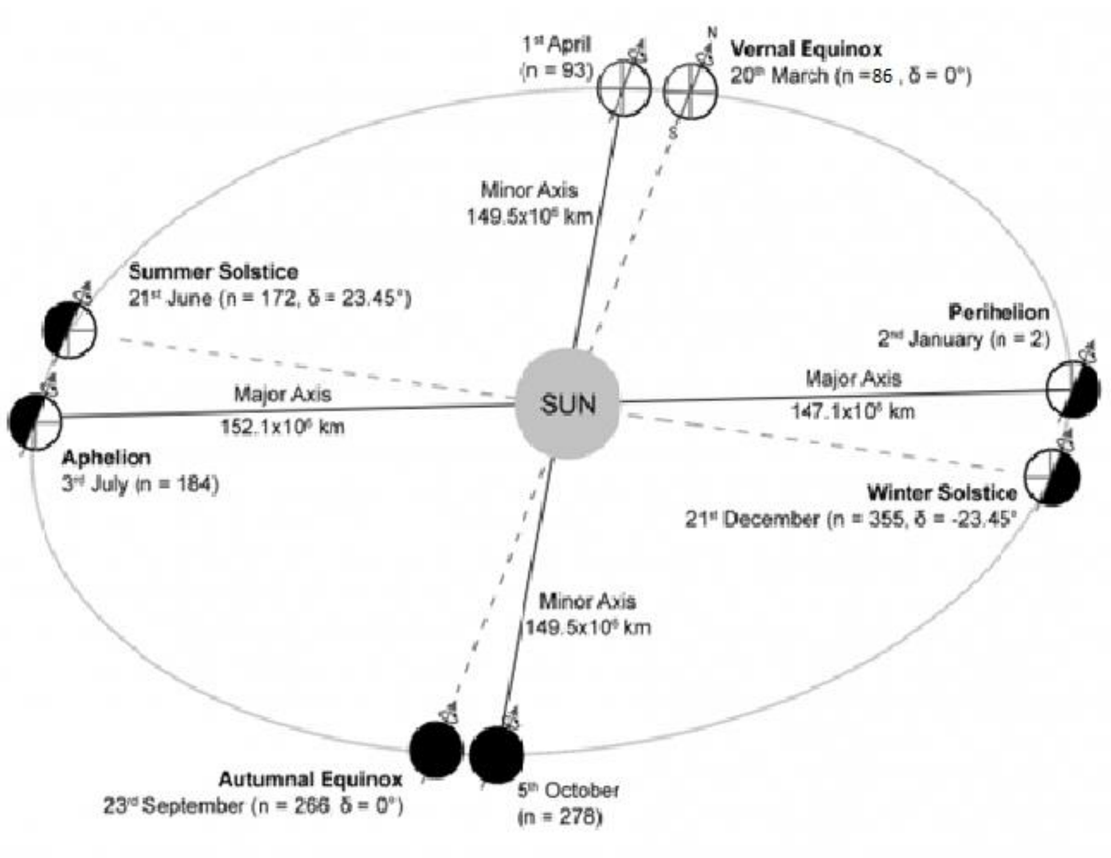

Figure 7: Earth orbit around Sun. Source: ITACA

The declination angle is driven by the equation 4:

$$\delta = 23{,}45 * \frac{pi}{180} * sin\left[2 * pi * \left(\frac{284 + n}{36{,}25}\right)\right] \quad (4)$$

The results of the equation varies between 23,45º (Summer solstice and tropic cancer) and -23,45º(Winter solstice and tropic Capricorn) as the figure 8 shows. This effect is important as the energy received by the surface is reduced if the point is not perpendicular, so the relative distance of a point from the point of maximum irradiance changes during the year and consequently so does the irradiance it receives.

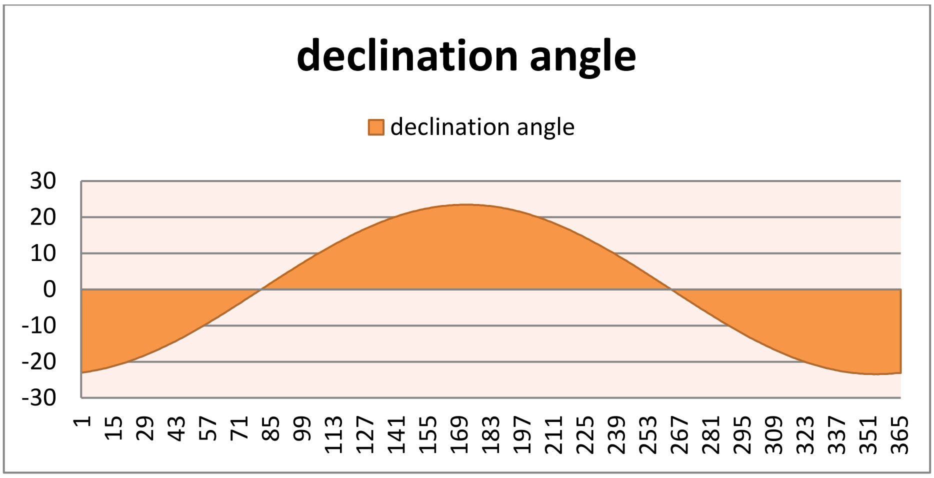

Figure 8: Declination angle along year. Source: own development

3.2.3 Cosine effect

The solar irradiance calculated with the equation 3 is only valid for one point in the whole earth, in order to make the project approximation more accurate it is necessary to take into account the effect of distance from the point P. The irradiance is going to suffer relevant reductions with distance and as the Earth´s has a spherical shape the distance is going to be defined by latitude(φ). For the same φ the sun irradiance is the equal considering the measure is performed at the same local time, so the main irradiance loss is going to be caused with the latitude difference that has a range of 90 to -90. Another factor that causes losses with respect to the point P is the hour angle(ω), it consists in the longitudinal distance from the point P. The ω strongly depends on several factors as day, local time, Local longitude and Standard longitude. The reduction of the sun irradiance is calculated via cosine effect being described in equation 5:

$$I_{\theta} = I_O * cos\theta = I_O * (\cos\varphi * \cos\delta * cos\omega + sin\varphi * \sin\delta) \quad (5)$$

The equation 5 will be applied to the different factor in order to obtain an average percentage of losses that can be applied for the next procedures:

- φ effect will produce a reduction of 36%.
- δ effect will produce a reduction of 4%.
- ω effect depends on several factors very dependent on specific location, as the calculations of this work are worldwide and excessive number of calculations will need to be performed, however the effect of ω will be taken into account considering that only 8 hours per day on average have a relevant irradiance.

3.2.4 Atmosphere effect

Another important factor is the effects of atmosphere, as it protects the human beings from a lot of radiation coming from sun and with the support of the clouds help to regulate the earth´s temperature making life possible. Figure 9 shows the different processes the sun's radiation suffers. The total amount of energy lost due to atmosphere effect is called Albedo and depends on the atmosphere composition that has been variant during the earth's history. In order to simplify the calculations, we will apply an Albedo of 30%, approximately the actual one, for all the periods that will be analyzed.

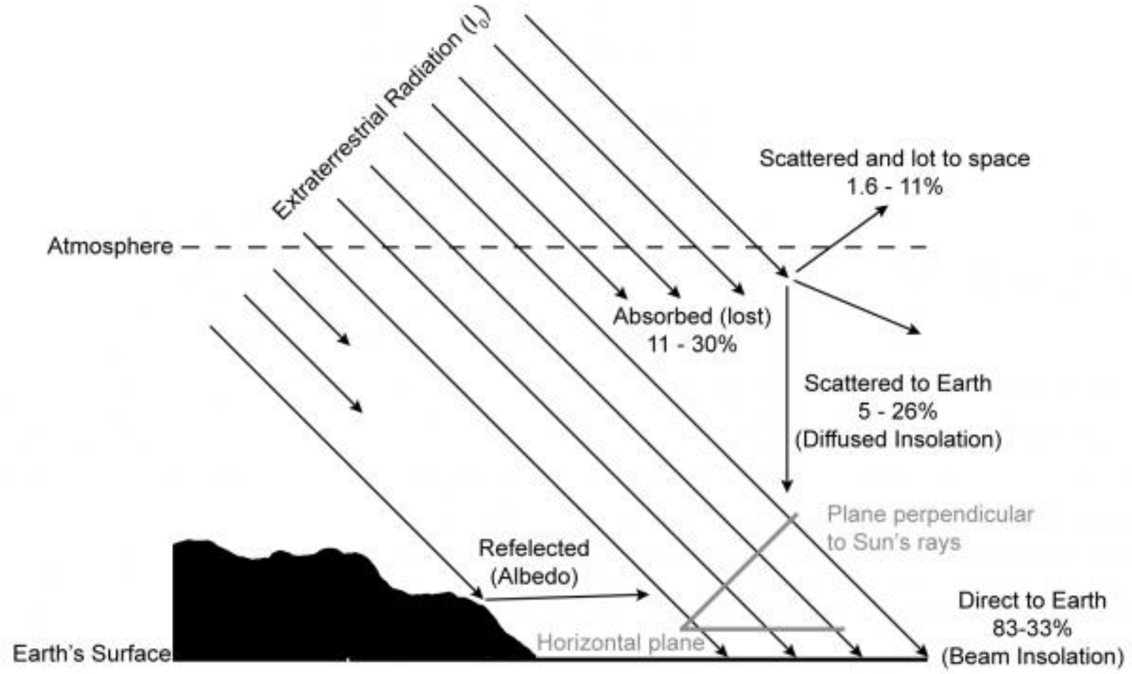

Figure 9: Atmosphere effect on solar radiation. Source: ITACA

3.2.5 Earth geometry

The calculation will continue defining the portion of the earth receiving sun´s irradiation. To do so it will be considered that the sun irradiates a disc characterized by the earth´s radius but only half of the earth surface will be receiving the sun energy making the surface receiving the sun irradiation the showed in equation (6) knowing that the earth´s radius used for engineering calculation is 6,371*10^6.

$$Surface\ recieving\ irradiation = \frac{pi * R_{Earth}{}^{2}}{\frac{4 * pi * R_{Earth}{}^{2}}{2}} \tag{6}$$

3.2.6 Final calculation

Applying all the factors stablished before an approximation of the sun energy reaching earth ($H_{Average}$)will be obtained by the equation (7):

$$H_{Average\ day} = I_{Solar\ constant} * (1 - \varphi_{Losses}) * (1 - \delta_{Losses}) * \left(1 - Albedo_{Average}\right) * Surface\ recieving\ irradiation * 8\ hours\ of\ relevant\ irradiance\ per\ day \quad (7)$$

Obtaining that $H_{Average\ day}$ is 2,3357 kWh/day $* m^2$ so $H_{Average\ year}$ = 852,53 kWh/year*m^2 or 3069 MJ/year*m^2.

3.3 Fossil fuels reserves calculation

During this chapter an approximation of the total potential energy stored within the earth in form of fossil fuels will be calculated. To do so some parameters must be fixed as constants for the following calculations.

The first one is the percentage of water in the earth which has slightly varied during the earth life due to the tectonic movements but will be considered constant at 70 % [9] for all the eras studied.

Another factor to be stablished is the percentage of sun energy that the plants are able to gather, as they will be the ones in charge of storing the energy incoming from the sun through the photosynthesis process. The efficiency of these process is very low having very slight variations depending on the plant species, also only half of the sun wavelengths can be used for this process so the energy stored is even lower but it can be stablished in an average of 1% for the terrestrial plants [10].

3.3.1 Coal formation process

The Coal is a solid fossil fuel with around 70% of its volume formed by carbonaceous material [11]. The formation process of coal last millions of years and is developed only if some geological conditions are fulfilled, for the process to begin swampy wetlands must be buried underwater, with the wetlands great big accumulations of vegetation are submerged and they star the decomposition process but they are isolated from the air and the stagnant water has a low content in oxygen slowing the decomposition process. Anaerobic bacteria interact with the dead vegetation matter during millions of years producing a partially decayed plant matter called peat. The peat may stay in the superficial layers or may be buried deeper dur to the tectonic movements. While the peat is buried more profound the pressure and the temperature increases the oxygen and the water are squeezed out of the matter increasing the density and the concentration of carbon. The different types of coal formed in an increasing time formation duration are [12]:

1. Peat carbon content >60%
2. Lignite carbon content 60-70%
3. Sub-Bituminous carbon content 71-77%
4. Bituminous carbon content 77-87%
5. Anthracite carbon content <87%

The majority of the coal reserves were formed during the Carboniferous (360-290 million years B.C.) located at the Paleozoic era [13]. Some other minor quantities were formed during the Permian and Mesozoic era but these last quantities are depreciable compared to the first one and will not be considered in the calculations.

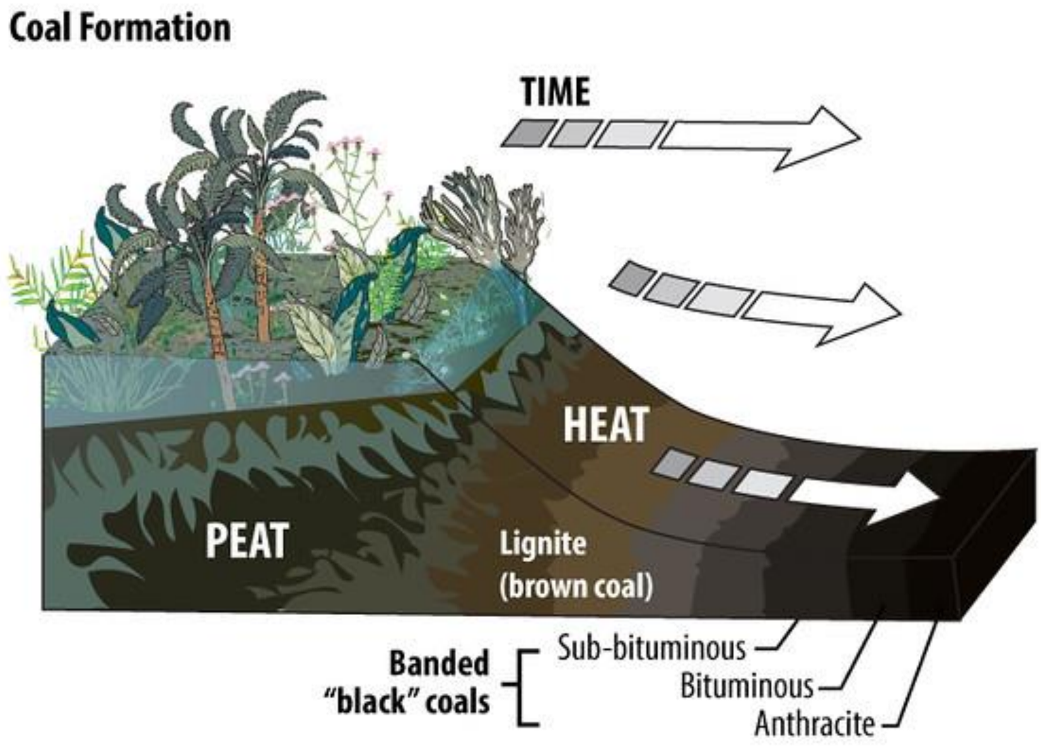

Figure 10: Coal formation process. Source: Smugmug

3.3.2 Coal Reserves approximation

The calculation of the energy stored in form of coal is highly dependent in the earth's land location during the era it was formed, Carboniferous. By looking at the figure 11 it can be observed that the land was much more concentrated than in actuality forming a massive unique continent, however the land parts located at the south pole were frozen making vegetal life hardly possible and should be removed from the calculations reducing the percentage of mass that is going to be taken into account. A simple estimation allows to fix the frozen lands as a value around 25-24% depending on picture, so it will be deduced that the 25% of the land percentage must be reduced reaching a land percentage of 22,5% of earth's surface.

Once the previous factors are stablished it is possible to calculate the total energy stored on earth in form of sun during earth's life by the equation 8:

$$Energy\ stored_{Coal} = H_{Average\ year} * Land\ percentage * plants\ efficiency\ of\ storage * Carboniferous\ duration * Earth´s\ surface \tag{8}$$

$$Energy\ stored_{Coal} = 3069\frac{\mathrm{MJ}}{\mathrm{year}*m^2} * 0{,}225 * 0{,}01 * (360 - 290) * 10^6 * 4 * pi * {R_{Earth}}^2$$

The equation 8 gives a result of 38700 EJ deducing the part already used described in Chapter 3.1 "Fossil fuels used during history" the actual energy reserves in form of coal reaches the quantity of 31158 EJ.

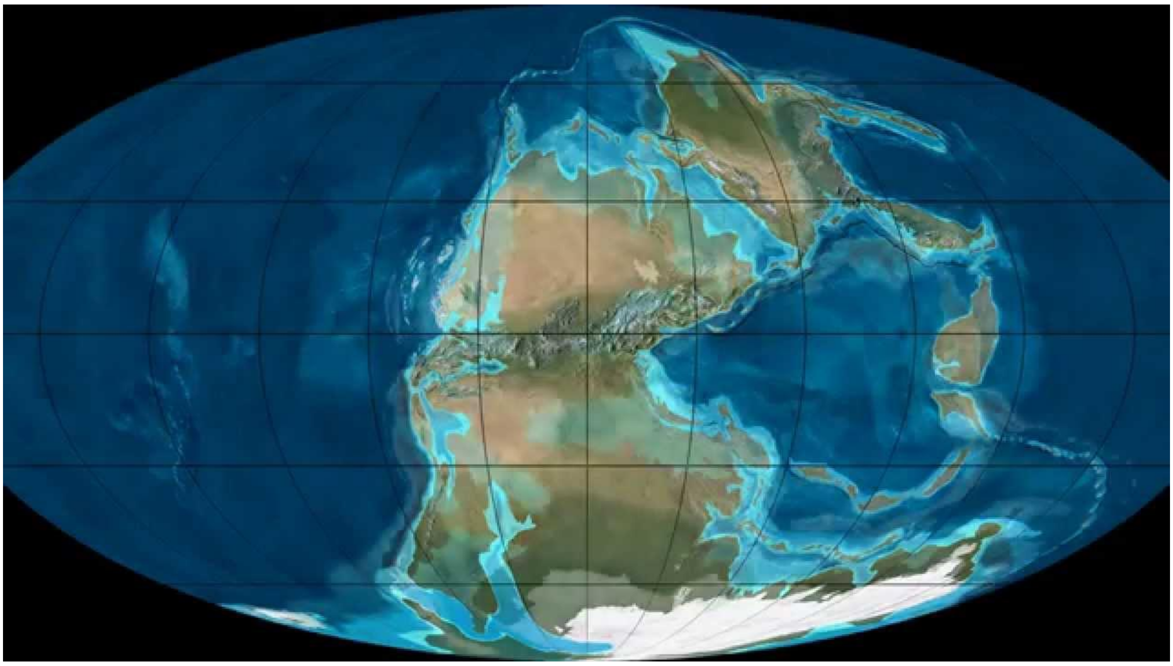

Figure 11: Carboniferous landmasses distribution. Source: Paleocast

3.3.3 Oil and Natural Gas formation process

The process of formation of Oil and Natural gas is almost the same, both surge from the degradation of organic matter in the sea floor where they are combined with inorganic matter creating a mud with high organic content, as happened in the coal formation process these organic matter is isolated from the air oxygen and the decomposition process is slowed allowing it to be buried before completely disappearing. If the deposits of organic matter reach 2-3,5 km deep the temperatures and the pressure allow them to transform into Kerogen that can be of different types depending on the source of the organic material. When the temperatures are between 90ºC and 160ºC Oil and gas are generated while if the temperatures are higher than 160ºC only gas is generated [14]. As oil is lighter than water it filtrates and is therefore lost unless there exist a layer of impermeable rock above the reserve. The spanning eras of these processes are well defined, it is known that 70% of deposits were created during the Mesozoic age (252-66) million years ago, 20% during Cenozoic and finally 10% in the Paleozoic.

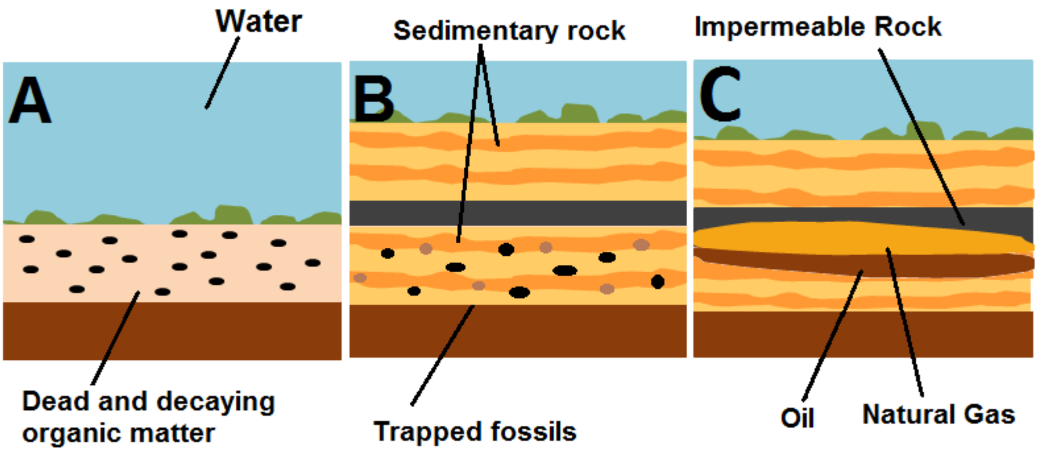

Figure 12: Oil and Natural gas formation process. Source: ENERGY EDUCATION

3.3.4 Oil and Natural Gas Reserves approximation

The process of creation of oil and gas is the same at the first stages so it is not possible to differentiate between the two in the type of calculations performed during these work as geological movements are not being analyzed therefore we will analyze both of them as a single sample. The geological analysis done in the Chapter 3.3.2 “Coal Reserves approximation” will be repeated but for a different era. The Mesozoic era is to extent and the tectonic masses moved along it making difficult to make similarity of the zones not suitable for life, however we can differentiate it in three different periods; Triassic (252-201 million years ago), Jurassic(201-145 mya) and Cretaceous(145-66 mya).

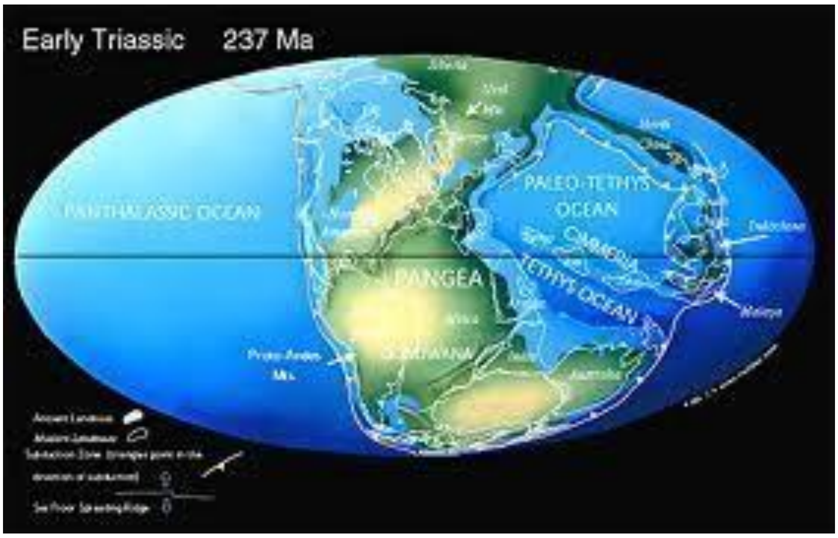

Figure 13: Triassic landmasses distribution. Source: Pinterest

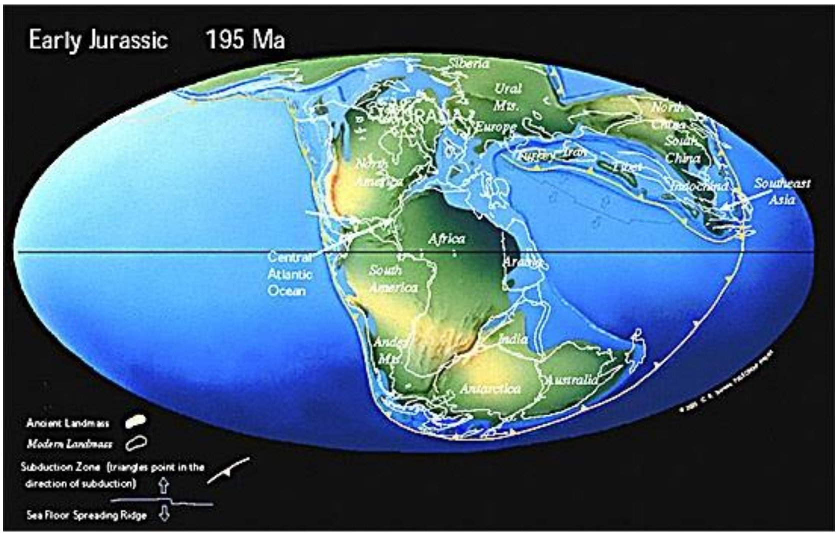

Figure 14: Jurassic landmasses distribution. Source: Pinterest

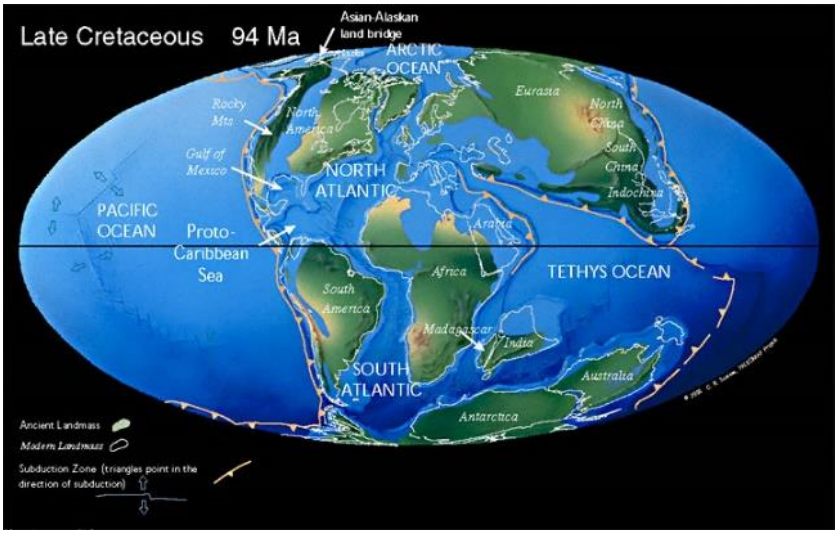

Figure 15: Cretaceous landmasses distribution. Source: Pinterest

A simple estimation allows to fix the percentage of land not suitable for life as follows:

- Triassic 31% reduced from the 30% average land percentage gives 20,7% suitable.
- Jurassic 26% reduced from the 30% average land percentage gives 22,2% suitable.
- Cretaceous 19% reduced from the 30% average land percentage gives 24,3% suitable.

Once these values are fixed it is possible to calculate the energy stored during these periods (9):

$$Energy\ stored_{Oil\ and\ Natural\ Gas} = H_{Average\ year} * plants\ efficiency\ of\ storage * Earth\acute{}s\ surface * (Land\ masses * Period\ duration)_{Triassic} + (Land\ masses * Period\ duration)_{Jurassic} + (Land\ masses * Period\ duration)_{Cretaceous} \tag{9}$$

Applying equation 9 it is obtained an approximation of 77753 EJ, however these quantity is only 70% of the total the total amount stored is 111075 EJ. Subtracting the part already used calculated in Chapter 3.1 "Fossil fuels used during history" the actual energy reserves in form of oil and natural gas amounts 100563 EJ.

3.3.5 End date for fossil fuels

To analyze the possible end date for each fossil fuel it is necessary to define a value for the consume, in Chapter 2 "World energetic situation" it was described how the fossil fuels usage is being reduced in the last two years, specially coal, however the demand is expected to suffer a high increase due to the developing necessities of two countries with high population density, China and India. Due to this uncertainty in the future energy share of fossil fuels the last known year demand (2015) will be applied for the three cases. As a reminder they will be shown in the table 1:

Energy source	Mtoe	EJ
Coal	3620	151
Oil	4620	193
Natural Gas	3120	131
Oil+Natural Gas	7740	324

Table 1: Reminder world energy production of fossil fuels. Source: Own development

Once assumed these consumes it is only necessary to divide the actual energy reserves of each kind by it, taking into account that the Oil and Natural Gas demand are going to be treated as a single one. The operation is described in equation 10:

$$Remaining\ years_{Fossil\ fuel} = \frac{Actual\ energy\ reserves_{Fossil\ fuel}}{2015\ consume_{Fossil\ fuel}} \tag{10}$$

Applied to coal (11):

$$Remaining\ years_{Coal} = \frac{31158\ \mathrm{EJ}}{151\ \mathrm{EJ}} = 206\ years \tag{11}$$

Applied to Oil and Natural Gas (12):

$$Remaining\ years_{Oil\ and\ Natural\ Gas} = \frac{100563\ \mathrm{EJ}}{324\ \mathrm{EJ}} = 310\ years \tag{12}$$

The value of Oil and natural gas should be highly reduced in reality as it only remains in the shale if there exist and impermeable rock that does not allow the oil and gas to be filtrated but geological conditions are not being analyzed during this project. It is also important to note that these are the possible reserves, but not all the reserves can be exploited, some could be placed at the sea floor being inaccessible or simply too expensive to exploit. As has shown the fossil fuels are produced in environments where there is no contact with the air, covered with water, meaning that they were deposited in the sea floor, due to tectonic movements during history land has emerged in some of these zones making the fossil fuels more accessible but it is reasonable to assume that most of the reserves will still be in the sea floor and therefore very expensive or impossible to exploit.

This increasingly limited quantity of resources demands the introduction of a new way of generating energy. The first option seems to be renewable energy due to its low cost and the fact that they obtain energy from unlimited resources as sun and wind, but the low energy density and their intermittence in the production makes impossible for them to substitute the fossil fuel with the actual technology. The only alternative capable to produce big amounts of energy in a constant way is the nuclear energy.

Chapter 4: Fossil fuels substitution by nuclear fission

In this chapter we will analyze the substitution of each individual fossil fuel by nuclear fission energy as well as the nuclear power plant (NPP) necessaries to perform this change and the effects on CO_2 emissions

4.1 Nuclear energy

The nuclear energy is defined by the Consejo de Seguridad Nuclear (CSN) as:

“The nuclear energy is the energy contained in the nucleus of an atom”

The atom is the smallest particle in which a chemical element can be divided while maintaining its properties. The atoms are formed by three elements, neutrons, protons and electrons. The first two are grouped forming the nucleus of the atom, in order to keep them together high forces are needed, in other words a great amount of energy is used to maintain the nucleus and this is the energy the NPP use to produce electricity when the energy is forced to be released. There exist two ways of obtaining this energy, fission and fusion, depending on the mass of the element.

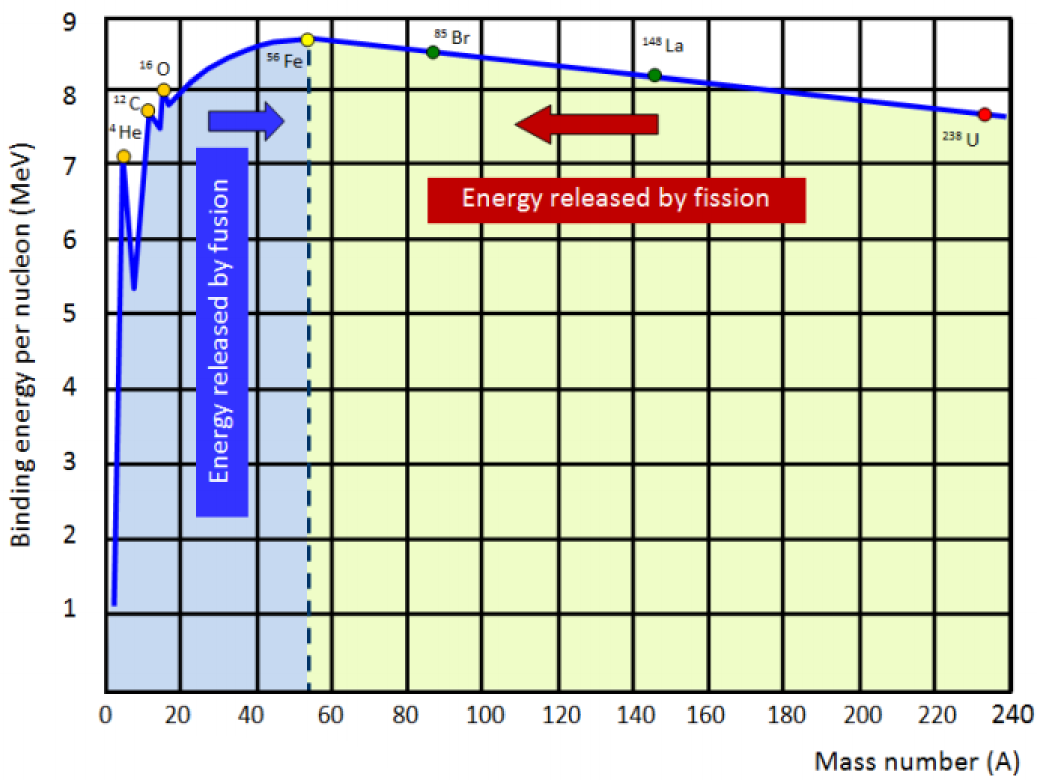

Figure 16: Binding energy of nucleon against mass number. Source: Schoolphysics

4.1.1 Nuclear energy history

The beginning of the nuclear history started in the ancient Greece where the first definition of an atom was made by the philosopher Democritus of Thrace in the fifth century BC. He postulated that everything was formed by elements called “atoms” being the smallest indivisible piece of matter.

Some millennia must pass until the next important discovery is made, It came by the hand of the English scientist John Dalton in 1803 BC which formulated an atomic theory summarized in the following points

- The matter is formed by indivisible, indestructible and extremely small particles called atoms.
- The atoms of a same element are identical, physically and chemically.
- The atoms of different elements are different physically and chemically.
- The chemical compounds are formed by a fixed combination of atoms.

The next contribution came from J.J.Thomson in 1904 with the discovery of the electron, he hypothesized that the atom was formed by a positively charged sphere with negative electrons placed at its surface making the atom electrically neutral.

Only a few years later in 1911 Rutherford concluded that the electrons where not placed on the sphere or nucleus but orbiting around it, being almost all the mass of the atoms concentrated in the nucleus.

In 1913 Niels Böhr developed his atomic model which said that the electrons moved following stable circular orbits around the nucleus, the radius of these orbits where defined by a quantum number. The electrons only absorb or emit energy when moving from one orbit to another in discrete energy proportional to that quantum number.

Some corrections were made to the Bohr model by Sommerfeld in 1916, in order to adapt the model to the relativistic mechanics, by theorizing that the electrons move at velocities close to that of light. The electric levels were also divided into sublevels and elliptical orbits were introduced.

Böhr’s model suffered another correction in 1926 by Erwin Schrodinger when he defined the electrons as waves. To localize electrons, he placed orbitals around the nucleus which were areas of space with a high probability of finding an electron within it.

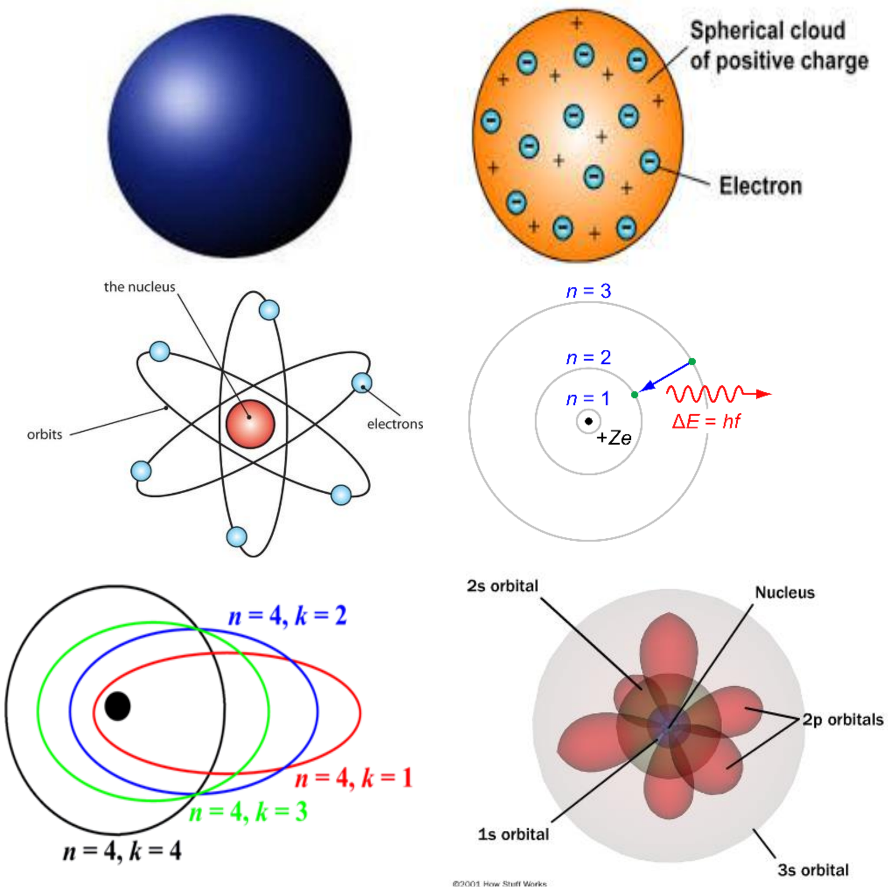

Figure 17: Different atomic models, from left to right and up to bottom. Dalton Thomson Rutherford Börh Sommerfels Schrodinger

In 1932 James Chadwick changed the nucleus concept with the discovery of the neutron eliminating the previous idea of a positive charged uniform sphere.

In parallel to the atomic model development, mineral containing Uranium was found by Henri Becquerel and studied by the Curie couple discovering that other materials such as, uranium, thorium, radius and polonium also emitted large amounts of radiation.

The possibility of generating energy through neutron beam to some elements appeared with the combination of the discoveries of artificial radioactivity by Joliot and Irene Curie and Einstein's relativity equation E=mc^2 which related energy and mass.

Sadly, the first use for this new way of producing energy was Hiroshima and Nagasaki bombs in 1945, it was necessary to wait until 1954 when Obsninsk nuclear power plant started to use nuclear energy for civil purposes.

4.2 Nuclear Fission

The nuclear fission is the process by which the atom nucleus of a heavy element is divided into two new atoms of a little less of half the original mass, generally this process is forced through a neutron beam. Great quantities of energy are released due to the effect of the mass defect generated. The mass defect is calculated with the equation 13:

$$\Delta m = \left[Z * \left(m_p + m_e\right) + (A - Z) * m_n\right] - m_{atoms} \tag{13}$$

Once the mass defect is calculated we use the Einstein´s mass-energy equivalence (equation 14):

$$E = mc^2 \tag{14}$$

As we can observe from the previous equation great quantities of energy are released with small mass because of the high order of the c. The energy is released in form of kinetic energy of the products generated during fission which is converted into heat while being stopped by different medium.

The most common fuels for nuclear fission are U_{235}, U_{238} and Pu_{239} but in order to produce the fission, some energy must be provided per nucleon (Critical energy) to overcome the binding energy, which consists in the amount of energy released if the nucleus was formed by the separate particles.

Target Nucleus	*Critical Energy* E_{crit}	*Binding Energy of Last Neutron* BE_n	$BE_n - E_{crit}$
U-238	7.0 MeV	5.5 MeV	−1.5 MeV
U-235	6.5 MeV	6.8 MeV	+0.3 MeV
Pu-239	5.0 MeV	6.6 MeV	+1.6 MeV

Table 2: Energy properties of fission fuels. Source: World nuclear

It is important to note that not all absorption will end as a fission reaction, normally only 85% does, the other will end as radioactive capture.

we will study the U-235 reaction as it is the most used nowadays, the fission reaction produces 200MeV on average. The total kinetic energy per Uranium-235 is, on average, 167MeV and emits 2,4 neutrons per fission each carrying 2 MeV giving approximately 5MeV of energy associated with the prompt neutrons. The following table shows in detail the energy values per U_{235} fission.

	MeV
Fission fragment kinetic energy	166
Neutrons	5
Prompt gamma rays	7
Fission product gamma rays	7
Beta particles	5
Neutrinos	10
Total	**200**

Table 3: Energy released in U-235 fission. Source: World nuclear

The main advantage of fission energy production is that it can be self-sustained by chain reaction that consist in the following; If the 2,4 neutrons produced in each fission find another fuel nucleus and collide with it they could cause more fission to take place producing another 2,4 neutrons that can multiply this process continuously.

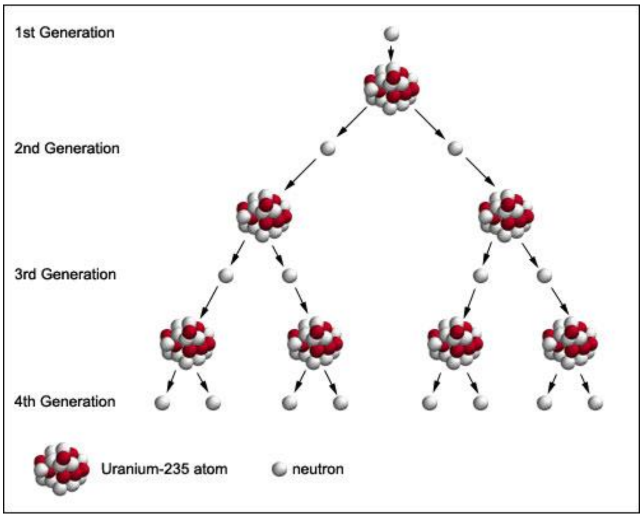

Figure 19: Chain reaction process. Source: Atomicarchive

The precedent picture shows how the resultant neutrons are exploited in order to continue the fission process without the energy cost of the first generation one. For the chain reaction to take place it is necessary to have enough U-235 together to make this process self-sustaining. To know if the chain reaction is table we need to look at the multiplication factor (k):

$$k = \frac{n\ in\ one\ generation}{n\ in\ the\ preceding\ generation} \tag{15}$$

k is a very important factor for nuclear power plant operator because it allows to change the reactor power when necessary. If this factor equals 1 the chain reaction can self-sustain in a controlled way called critical state, if k<1 the number of fissions are suffering a reduction (subcritical state) which could lead to the shutdown of the energy generation in an extreme case and finally if k>1 we are in a supercritical state scenario where the number of fission are increasing, supercritical state is dangerous as the reactions can get out of control, uncontrolled this state can generate enough energy to cause large explosions.

In the NPP the chain reaction takes place in a pressure vessel filled water pool in order to control temperature and slow down the neutrons to control the chain reaction as the water is a neutron moderator. Another measure is performed to control the chain reaction, control rods made of neutron absorber materials, as boron, are introduced or extracted to manipulate the chain reaction and heat generated depending on the NPP necessities.

Although uranium 235 is the most used fuel in NPP due to its properties in nature it is found in vary low concentrations, in uranium mineral only 0,7% is U-235 making necessary to enrich the mineral until reaching 3-5% concentrations in order to make the process efficient.

The most common type of NPP are boiling water reactor and pressurized water reactor:

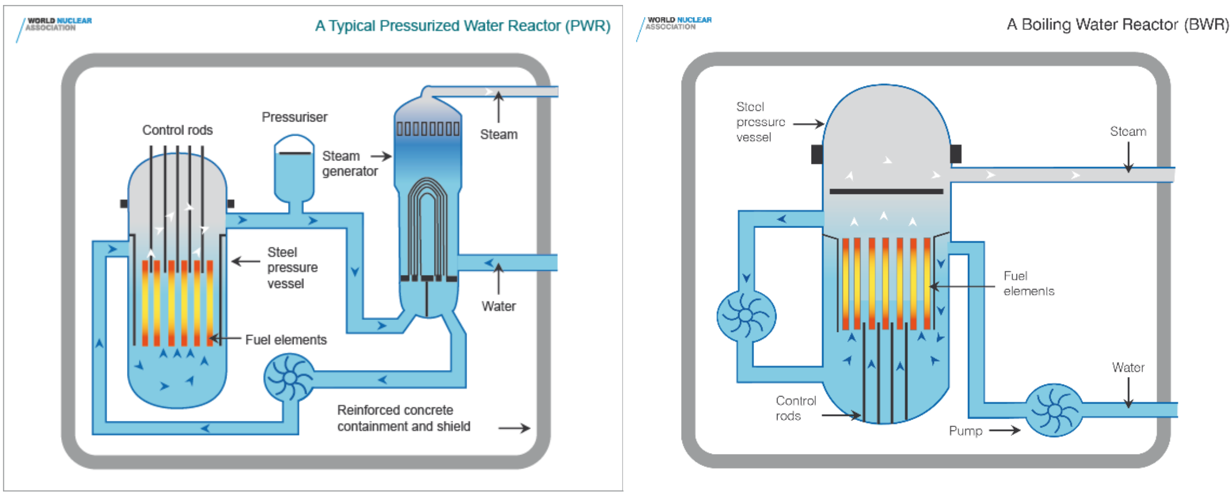

Figure 20: PWR and BWR system. Source: World nuclear

Actually, there are 450 NPP operating in the world with a total net electrical capacity of 4 TW as the figure 23 shows:

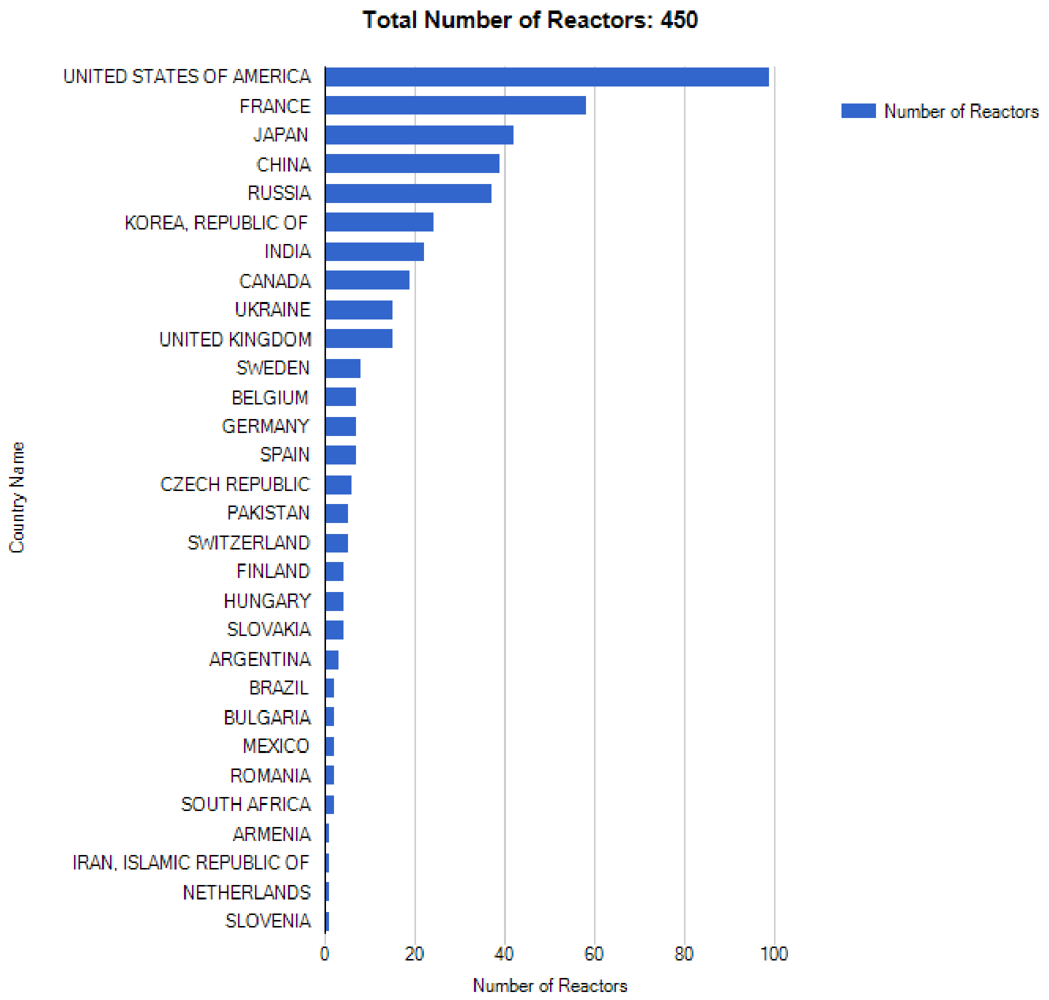

Figure 21: Operating nuclear reactors. Source: IAEA Pris

4.2.1 Nuclear Fission Radiation Emission

The main constraint of nuclear fission is the public opinion about it, it is considered as an extremely dangerous way of producing energy. These perception is based in one hand in real events and knowledge and in the other hand in myth and false information, so a deep analysis in the radiation emissions of a NPP and the hazard they represent must be performed to decide if the risk of this way of producing energy is too high to implement it.

The public perception about radiation is mainly driven by the following factors:

The radiation represents a relatively new danger and the first introduction of it to the society was in form of the nuclear weapons released in Nagasaki and Hiroshima in 1945 which caused a huge shock worldwide. Also, it is a big concern the fact that the radiation is nondetectable by the human being until it reaches levels highly above lethal levels.

The way the radiation causes damage is very particular and can be divided into three types:

1. Displacements of atoms and electrons (ionization).
2. A very large release of energy in a small volume, normally in form of heat.
3. Production of impurities in the atomic structure.

Mostly 4 types of radiation are released during the fission process:

- Alpha radiation (α):

  α radiation is emitted in form of a helium nuclei (^4_2H), it consists in a particle of mass of 4 amu and a double positive charge. As these elements have an electrical charge they experience coulomb barriers and lose their energy in form of heat while interacting with the medium placed around them.

  The coulomb barrier is calculated with:

  $$F = k_{constant} * \frac{q * q'}{r^2} \tag{16}$$

  By looking at the equation it can be observed that the charged elements are constantly under the effect of the electrons of the medium in relation with the distance between them allowing to make an exact calculation of the summary of forces for every medium.

  But the important parameters while studying the radiation are the linear energy transfer(LET) and the range (R):

  $$LET = \frac{dE}{dx} \tag{17}$$

  $$R = \int_0^{E_0} \frac{dE}{LET} \tag{18}$$

  So, the LET consist in the energy deposition per distance travelled and the R is the distance travelled by the α particle.

  The combination of the mass and the double charge give a very short range being the thickness of a sheet of paper enough to stop α radiation.

  The α radiation causes atom displacement ionization and heat deposition due to its short R.

- Betha radiation (β):

  β radiation is emitted in form of an electron (e^-) with a mass of 5,5*10^{-4} amu and a single charge. As can be observed the mass of the electron is very low compared to the helium making necessary to consider the deviations suffered in the electron path but fortunately even if every electron path varies they have a predictable spread of values.

  The mass and the charge are smaller than in α but the mass reduction is much higher than the charge ($m_p \gg m_e$) causing that the negative acceleration caused by the collisions is much greater and therefore the R is even smaller than in α. Despite the variances in R a thin layer of metal is enough to deal with this type of radiation.

β radiation causes displacement of atoms and ionization. It can also cause localized heat deposition in some cases.

- Gamma radiation (γ):

  γ radiation is emitted in form of photons and so it interacts mainly with electrons only. Due to this fact Gamma radiation only causes ionization, not atom displacement. The γ radiation interact with electrons in three different ways. For any of these interactions to occur the photon must hit an electron otherwise the photon can travel any distance, a side effect of the great R is that the heat deposition occurs over huge distances.

  1. Photoelectric effect. Energy of the photon is completely converted into kinetic energy of an electron, only this interaction completely absorbs all radiation.
  2. Compton effect. Only part of the photon energy is converted into electron kinetic energy reducing correspondingly the radiation energy and changes the direction of the photon.
  3. Pair production. Photon energy is converted into mass and kinetic energy of an electron positron pair. The pair production reaction can only occur for the photons whose energy exceeds 1,022MeV which is twice the electron mass. If the reaction occurs two photons of 0,511 MeV are generated called annihilation gammas.

  R is the average of a great sample and has values highly greater than α and β.

- Neutrons:

  Neutrons are emitted during the fission, as explained before 2,5 on average and they may cause additional radiation. The R of the neutrons is defined by the mean free path (λ) and this last one is completely dependent on the neutron energy and material composition.

  The neutrons cause a high number of atom displacements and cause indirect radiation damage as they can cause reactions able to generate fission, all the above radiations and nuclei impurities.

  In the NPP the neutron energy is very high giving as a result a very large R making the neutrons a very dangerous biological hazard.

The quantity of radiation is measured on rad (radiation absorbed dose) which consist in the energy deposited per unit of mass or in the SI unit gray (Gy) $1\ Gy = 100\ rad$ (not to be confused with radians). In order to take into account which type of radiation is producing the exposure the quality factor (QF) concept is introduced so the dose equivalent (H) may be calculated.

$$H(rem) = QF * dose(rad)$$
$$H(Sv) = QF * dose(Gy) \tag{19}$$

The table 4 shows the different QF depending on the source:

Type of radiation	Quality factor (Q)
X-, gamma, or beta radiation	1
Alpha particles, multiple-charged particles, fission fragments and heavy particles of unknown charge	20
Neutrons of unknown energy	10
High-energy protons	10

Table 4: Quality factor of different types of radiations. Source: NRC

4.2.2 Biological effect of Nuclear radiation

The effect of radiation is not the same in all materials, it depends on the molecular composition of the subject that is receiving it. Radiation tends to be more susceptible to damage the following compositions in decreasingly damage:

1. Van der Waals bond.
2. Covalent bond.
3. Ionic bond.
4. Metallic bond.

Being the more characteristic bond of the biological tissue the covalent bond it can be deduced that biological life is highly affected by radiation.

The radiation damage may be done in a direct and an indirect way being responsible of 20% and 80% of the damage correspondingly.

The tissue is affected directly when the radiation interacts with the cell nuclei breaking important molecular chains such as DNA, normally this type of damage is non-repairable.

Indirect effects consist in the break of less critical particles as H_2O into reactive parts, being some of them very dangerous as H_2O_2, that reacts chemically with the DNA, proteins or other vital molecules. As the damage is not instantly delivered the body defenses have some time to reduce the effects of the damage dealt but the damage is greater proportionally to the range of differentiation of the cell affected being the more severe the lymph and the less important the muscular ones. Table 5 shows whole body radiation effects depending on the dose:

Some comparative whole-body radiation doses and their effects	
2.4 mSv/yr	Typical background radiation experienced by everyone (average 1.5 mSv in Australia, 3 mSv in North America).
Up to 5 mSv/yr	Typical incremental dose for aircrew in middle latitudes.
9 mSv/yr	Exposure by airline crew flying the New York – Tokyo polar route.
10 mSv	Effective dose from abdomen & pelvis CT scan.
20 mSv/yr	Current limit (averaged) for nuclear industry employees and uranium miners. (In Japan: 5 mSv per three months for women)
50 mSv	Allowable short-term dose for emergency workers (IAEA).
100 mSv	Lowest annual level at which increase in cancer risk is evident (UNSCEAR). Above this, the probability of cancer occurrence (rather than the severity) is assumed to increase with dose. No harm has been demonstrated below this dose. Allowable short-term dose for emergency workers taking vital remedial actions (IAEA). Dose from four months on international space station orbiting 350 km up.
250 mSv	Allowable short-term dose for workers controlling the 2011 Fukushima accident, set as emergency limit elsewhere.
350 mSv/lifetime	Criterion for relocating people after Chernobyl accident.
500 mSv	Allowable short-term dose for emergency workers taking life-saving actions (IAEA).
1,000 mSv short-term	Assumed to be likely to cause a fatal cancer many years later in about 5 of every 100 persons exposed to it (*i.e.* if the normal incidence of fatal cancer were 25%, this dose would increase it to 30%). Highest reference level recommended by ICRP for rescue workers in emergency situation.
5,000 mSv short-term	Would kill about half those receiving it as whole body dose within a month. (However, this is only twice a typical daily therapeutic dose applied to a very small area of the body over 4 to 6 weeks or so to kill malignant cells in cancer treatment.)

Table 5: Radiation effects on human body. Source: World nuclear

The table 6 shows the effect of high radiation doses:

Table 3. Signs and Symptoms of Acute Radiation Sickness in the Three Phases after Exposure.*

Prodrome, According to Exposure Level	Latency†	Illness‡
Mild (1 to 2 Gy) Vomiting; onset, 2 hr	Duration, 21–35 days; lymphocyte count, 800–1500/mm³	Fatigue, weakness; mortality, 0%
Moderate (2 to 4 Gy) Vomiting, mild headache; onset, 1–2 hr	Duration, 18–35 days; lymphocyte count, 500–800/mm³	Fever, infections, bleeding, weakness, epilation; mortality, ≤50%
Severe (4 to 6 Gy) Vomiting, mild diarrhea, moderate headache, fever; onset, <1 hr	Duration, 8–18 days; lymphocyte count, 300 to 500/mm³	High fever, infections, bleeding, epilation; mortality, 20–70%
Very severe (6 to 8 Gy) Vomiting, severe diarrhea, severe headache, high fever, altered consciousness; onset, <30 min	Duration, ≤7 days; lymphocyte count, 100 to 300/mm³	High fever, diarrhea, vomiting, dizziness, disorientation, hypotension; mortality, 50–100%
Lethal (>8 Gy) Vomiting, severe diarrhea, severe headache, high fever, unconsciousness; onset, <10 min	No latency; lymphocyte count, 0 to 100/mm³	High fever, diarrhea, unconsciousness; mortality, 100%

* Data are adapted from the International Atomic Energy Agency.[20]
† Lymphocyte counts in the latency phase represent the range of values that may be seen 3 to 6 days after radiation exposure.
‡ Mortality estimates are for patients who do not receive medical intervention.

Table 6: Acute radiation effects. Source: New england journal of medicine

4.2.3 Nuclear safety

The nuclear energy is the energy source with the highest security standards because of the potential damage it can cause to the environment and the humans. The number of nuclear accidents during history is minimum compared to other sources, being the three most important Chernobyl, Three mile island and Fukushima. Nevertheless the impact of a possible incident where radiation material is released has completely conditioned the nuclear energy development.

The objective of nuclear safety is to protect the population, environment and workers of the NPP of the risks of nuclear energy limiting as much as possible the probabilities of accidents and the effects of them if they cannot be avoided. In order to do so a severe control is performed over all the steps a NPP must fulfill to operate. Each country has its own legislation and specifications, however, there exist some basic principles applied worldwide based in the document published in 1971 by the united states government "General Design Criteria for Nuclear Plants" in the appendix A of the 10CFR50[15].

The Nuclear safety is based in 4 principles:

1. Defense on depth

   It consists in placing several barriers between the radioactive material of the reactor nucleus and the ambient while assuring the integrity of the barriers in case of operation failure and assure the necessary security systems to limit the accident effects until reaching acceptable levels.

   The barriers are:

   1. The uranium oxide generated by the fuel and the fuel pellets containing it.
   2. The cladding.
   3. The vessel and the pipe system that constitute the pressure barrier of the cooling system of the reactor.
   4. The containment vessel.

   In addition to this thee barriers 3 security levels are designed:

   1. The reactor must be stable and secure by design.

   2. An analysis of failures affecting normal operation called Deterministic analysis, the failures the NPP should be able to withstand are denominated Basis design accident. Some of the accidents a nuclear plant should withstand are fire, flooding, missile, earthquake, double ended guillotine break or loss of coolant analysis (LOCA). In order to withstand these possible accidents several safety systems must be installed, these systems must be redundant, physically separated and diverse to assure its functioning. They must be able to shut down the reactor (Control rods usually made by boron) remove the decay heat (residual heat removal system or isolation condenser) relieve the

pressure (safety valves) and maintain reactor coolant inventory (emergency core cooling system).

3. At last all possible situations or risk source are defined analyzing if they may lead to core damage and radiation release. These analysis is called Probabilistic safety analysis (PSA). Once PSA is performed containment structures necessaries to reduce the effects of core damage accident are defined.

2. Quality assurance

   Quality assurance is a basic element of nuclear safety in charge of to verify that all the elements, systems and structures are going to fulfill its design properties. The elements of a NPP are classified by the importance of their security function and the quality requirements and test frequency are stablished following the classification.

3. Human factor. Qualified personal

   The personal of a NPP must have a training and formation adequate to the function they perform and have the material necessary to assure the correct actuation of workers and to limit the effects of a human error. The controls and the design of the nuclear plant try to assure the security in case of a severe human error but an appropriate formation is the biggest guarantee for minimizing the failures that are going to happen eventually in any installation.

4. Safety culture

   It consists in the attitude of prioritizing the security over all other things to do so it is necessary the dedication and responsibility of all the personal that influence the NPP security. This attitude demands a constant concern.

Even with all the elements described before the accidents are an inevitable issue as they will happen sooner or later, to classify the accidents according to their magnitude the International Nuclear and Radiological Event Scale (INES) scale is utilized. The INES is a scale of 7 levels that imitates the Richter scale used for earthquakes, it is showed in figure 18, being level 7 the maximum consisting in a core damage accident with major release of radioactive material and 0 the minimum as a slight deviation of normal operation without consequences.

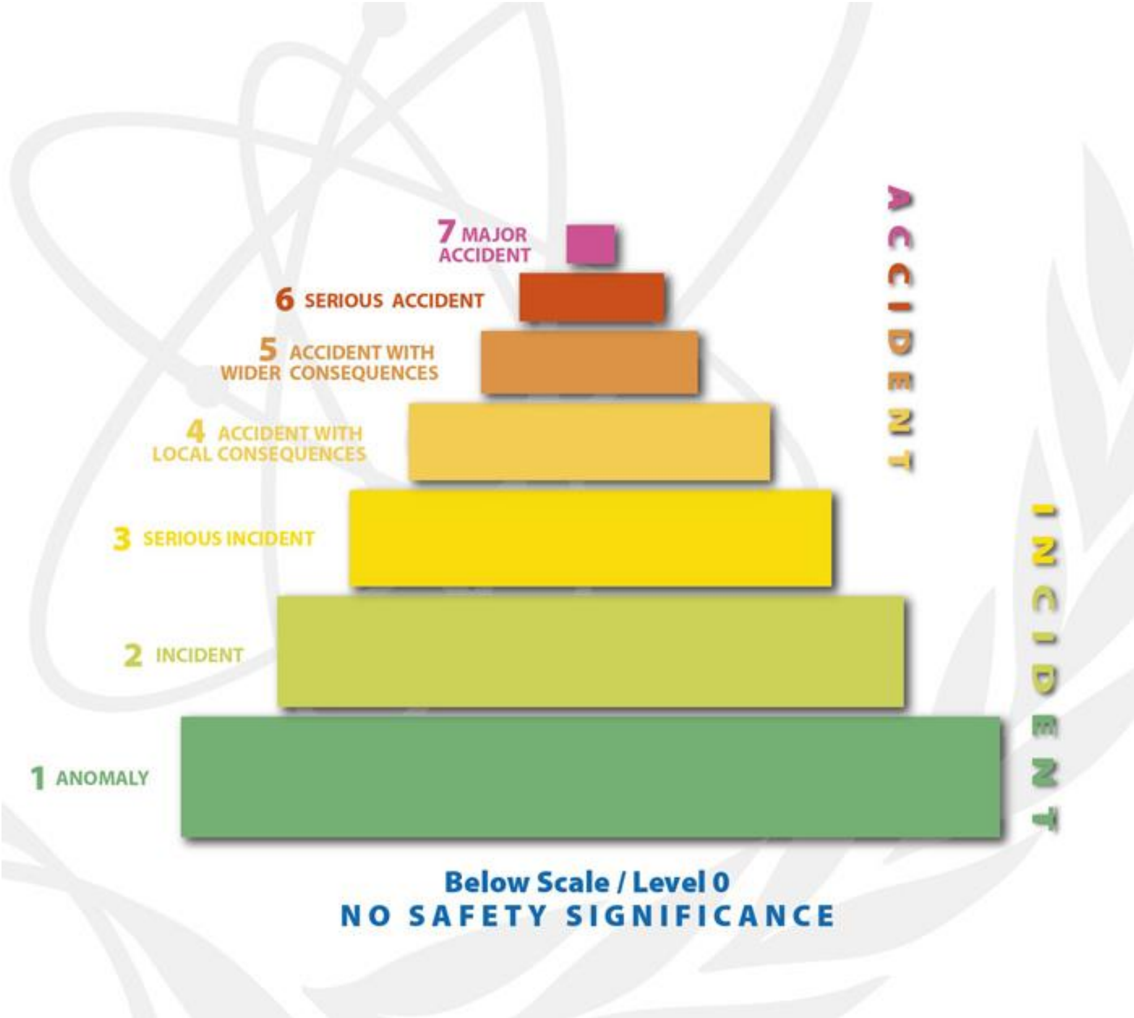

Figure 18: INES scale. Source: IAEA

For providing practical example the Three mile island accident is classified 5 while both Chernobyl and Fukushima are level 7. The fact that the Fukushima accident is considered as severe as the Chernobyl accident while no direct deaths were caused shows the great development of the security systems for NPP.

The probability of a core damage accident is very low but as the consequences are so severe a great quantity of analysis to determine the core damage frequency are performed. The NRC stablish that the reactor designs must assure a core damage frequency (CDF) of $1*10^{-4}\frac{CD}{years}$ but the newest NPP operating nowadays have a CDF of $1*10^{-6}\frac{CD}{years}$ and this value is expected to be reduced to $1*10^{-7}\frac{CD}{years}$ in the next decade. In Europe the new nuclear plants are required to have a CDF of $1*10^{-6}\frac{CD}{years}$ [16].

4.2.4 Nuclear waste

During all the different steps (Mining, Processing, Use and Reprocessing) developed in a NPP waste is generated, all energy sources produce waste during their operation but unlike the others nuclear waste is radioactive, making it a risk for human life and the environment. The NPP take responsibility for the waste they generate in both security and costs, however as the fission product generates great amount of energy with small quantities of fuel due to the great energy density of Uranium (3 kg of enriched uranium allows the operation of a 1 GW NPP for one day) the waste amount generated is also small and it´s volume can be reduced through incineration compaction or trituration. All operating nuclear plants generate 7930 tonnes of waste yearly.

Any material that is radioactive or has been contaminated by radiation is considered as radioactive waste. The half-life concept, applied to radionuclides, is necessary to understand the different wastes classifications, it is the time necessary for half of the atoms of an element to decay and as a direct consequence reduce the radioactivity also to the half. The type of radiation the radionuclides emit varies along the half-life, long life ones usually emit α and β with very low R and therefore easy to handle while short life tend to emit γ with the containment difficulties this type of radiation suppose. It is important to note that all radioactive elements are going to convert into non-radioactive waste as time passes but the time needed for this transformation can vary from decades to hundreds or even thousands of years. Table 7 shows the half-life of the main radioactive nuclides:

Nuclide	Half-life (years)
U_{234}	$2,5 * 10^5$
U_{235}	$7 * 10^8$
U_{236}	$2,3 * 10^7$
U_{238}	$4,5 * 10^9$
Np_{237}	$2,1 * 10^6$
Pu_{238}	$87,7$
Pu_{239}	$2,4 * 10^4$
Pu_{240}	$6,6 * 10^3$
Pu_{241}	$14,3$
Pu_{242}	$3,7 * 10^5$
Am_{241}	$432,7$
Am_{243}	$7,4 * 10^3$
Cm_{243}	$29,1$
Cm_{244}	$18,1$
Cm_{245}	$8,5 * 10^3$
Cm_{246}	$4,7 * 10^3$
Se_{79}	$1,1 * 10^6$
Sr_{90}	$28,79$
Zr_{93}	$2,1 * 10^5$
Tc_{99}	$1,5 * 10^6$
Pd_{107}	$6,5 * 10^6$
Sn_{126}	$1 * 10^5$
I_{126}	$1,6 * 10^7$
Cs_{135}	$2,3 * 10^6$
Cs_{137}	$30,1$

Table 7: Half-life of radioactive nuclides. Source: Own development

The decay of radioactive nuclides is exponential, meaning that during the first and most dangerous years the activity is highly reduced while a lot of time must pass later, as figure 19 shows:

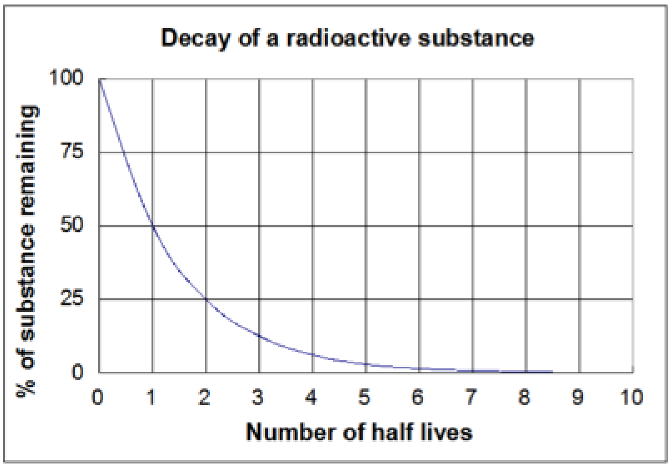

Figure 19: Radioactive decay. Source: Energyeducation

Radioactive waste does not come only from NPP but also from medical, agricultural, investigation and military usages.

The nuclear radioactive waste is classified in the following types by World nuclear:

- Very low level waste (VLLW)
  Materials with radioactive levels that are not harmful for humans nor environment, they are usually generated during the mining and milling process. Not special treatment is necessary for this type of waste in most countries.
- Low level waste (LLW)
  It is the most common type of waste supposing 90% of volume while only 1% of the radioactivity of total waste, it is mainly composed by contaminated material such as clothing, instruments, filters, etc. Due to the radiation composition explained before no special treatment is used during transport and handling.
- Intermediate level waste (ILW)
  This type of waste accounts 7% of the volume and 4% of the radioactivity of all waste and comprises material from reactor dismantling. A little amount of heat is generated due to decay but not enough to take special measures to deal with it while some shielding is required during transport and handling.
- High level waste (HLW)
  HLW constitute 3% of volume and 95% of radioactivity of all radioactive waste, it is composed by the spent fuel or the remaining of fuel reprocessing process both containing transuranic elements and fission products. This type of waste is the more dangerous and the biggest issue of NPP operation. They produce enough heat (>2Kw/m^3) to make necessary cooling and shielding for transport and handling. The spent fuel that is the main source of HLW still contains about

half the original energy content in form of U-235 and plutonium, undergoing a reprocessing process 25-30% more energy could be obtained from the same amount of fuel while reducing by 85% HLW and reducing the half-life of remaining HLW. The figure 20 shows the steps and the products of a reprocessing process.

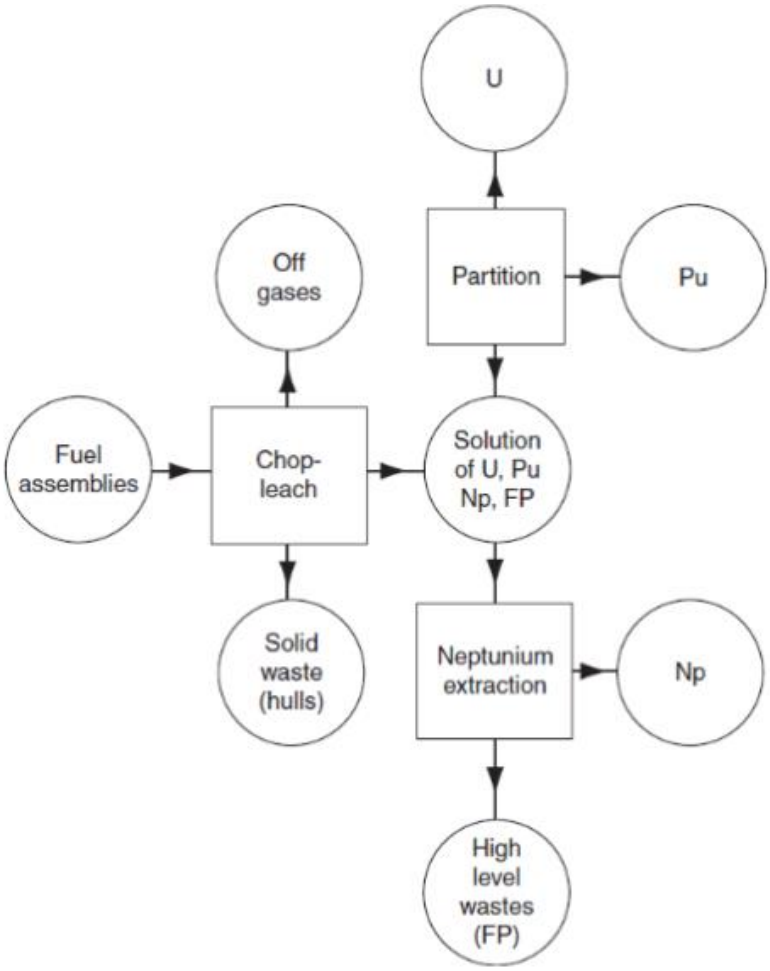

Figure 20: Reprocessing process. Source: Nuclear energy and introduction to the concepts, systems and applications of nuclear processes Murray 2009

The waste classification is used to determine how to manage the waste and where to deposit it once it has no longer use. Usually LLW and ILW are disposed in near surface structures while the HLW need a storage time of around 40-50 years at nuclear facilities in a storage pond or a dry storage unit until reducing the radioactivity and heat to 1%, the point where they are moved to deep geological facilities.

4.2.5 Public opinion on nuclear energy

The public opinion is the main constraint the nuclear power has if it wants to grow there exist a reticence in the society towards this type of energy worldwide caused partially by past events/accidents and a general lack of information about it.

The first introduction of the nuclear energy to the world was with the two atomic bombs that exploded in Nagasaki and Hiroshima showing the huge amount of energy that the nuclear energy can release for the worst purpose possible. The impact this event caused was enough to practically end the II World war and left a permanent reminder of the destructive possibilities that this energy can cause. But the event that is normally associated and utilized against nuclear energy is the Chernobyl accident, mainly caused by the human factor and deficiencies in the security design, and the consequent radioactive release produced by it with terrible effects on human's life not just in the accident location but in all the spread area. It is common material to see documents and pictures of the terrible effects of this accident most of them of questionable reliability. Recently the Fukushima accident made the society doubt about the security of NPP even though the authorities informed that no direct deaths were caused because of it.

In the end society is the one that must decide whether if the nuclear energy is going to be used or not but in order to make a fair decision it is necessary to have all the available information. The table 8 shows the main arguments in favor and against the nuclear energy:

In favor	Against
It is the only actual alternative to the fossil fuels to provide a big and constant energetic production without emissions	The main part of fossil fuels and therefore emissions are not used to produce electricity so they cannot be substituted by nuclear energy
The renewables energies are not able to produce enough energy to support the system	The amount of Uranium is limited and even if quantity necessary to operate NPP is very low it will be eventually consumed
Countries as USA, France or South Korea are investing in nuclear energy	The nuclear waste continues to be a hazard for human life and environment during long time periods
Is economic producing the kWh at very low cost	Not competitive as the lifetime of a NPP is of 50-60 years so new plants must be built at high prices after only a few decades of performance
The security has greatly improved during the past decades reducing the probability of accidents and the effects if it cannot be avoided	It supposes a great risk to society, even if the security stands are very high, due to its great damaging potential and the accidents are eventually going to happen

Table 8: Nuclear fission energy discussion. Source: Own development

4.3 Fossil fuels substitution calculation

In this chapter an analysis of the integration of NPP in the energy production system in substitution of the fossil fuels will be performed. However, some parameters must be stablished before realizing this analysis.

4.3.1 Calculation parameters

- End use energy substituted

The sources of energy are used in several ways, some direct as heat generation and others more complex as electricity generation, the traditional fuels have a great energy density and their usage does not require an elaborated manipulation, for example coal is directly burned to generate heat without the necessity of elaborated safety systems. But these direct and easily managed ways of exploiting the potential energy of the sources is not viable with nuclear energy, it seems ineffective and dangerous to utilize it in other way that generation of great quantities of electricity in NPP. As a consequence, the only percentage of fossils fuels that will be replaced is the one destined to electricity generation, being these percentage only a small amount of the total, however the electrification is estimated to increase greatly in the approaching years making the substitution sample greater if this analysis is performed again in some years.

- Capacity of new NPP

The next step in the calculation is to define some standards for the NPP that we are going to use. To stablish these standards, we will use the general data about the NPP working nowadays.

Reactor Type ▲	Reactor Type Descriptive Name	Number of Reactors	Total Net Electrical Capacity [MW]
BWR	Boiling Light-Water-Cooled and Moderated Reactor	75	72941
FBR	Fast Breeder Reactor	3	1400
GCR	Gas-Cooled, Graphite-Moderated Reactor	14	7720
LWGR	Light-Water-Cooled, Graphite-Moderated Reactor	15	10219
PHWR	Pressurized Heavy-Water-Moderated and Cooled Reactor	49	24598
PWR	Pressurized Light-Water-Moderated and Cooled Reactor	294	276965
Total		**450**	**393843**

Table 9: Operating reactors by type. Source: IAEA Pris

The most frequent NPP observed in the table 9 are BWR and PWR being 75 and 294 respectively, taking these two types as reference an average electrical capacity is going to be calculated for each kind giving a result showed in the table 10:

	BWR	PWR
Average electrical capacity per plant (MW)	972	942

Table 10: Average electrical capacity of the two most common types of nuclear power plants. Source: Own development

It can be observed that both have a capacity close to 1 GW so for calculation simplicity we will use this as the capacity basis.

It is also necessary to take into account that the NPP does not always operate at its maximum capacity so we will introduce the energy availability term. The energy availability is the ratio between the energy theoretically produced and the energy that the available capacity has actually produced as explained in equation 20.

$$EAF = \left(\frac{Reference\ energy\ generation - planned\ losses - unplanned\ losses - external\ losses}{Reference\ energy\ generation}\right) * 100 \quad (20)$$

The EAF world average is 76,8%.

Finally, the energy generated per NPP is calculated using the following equation:

$$Energy\ generated\ per\ NPP = Average\ electrical\ capacity * EAF * 24 * 365 \quad (21)$$

The result obtained is that every NPP generates 6728 GWh.

- Cost and time of construction of NPP

The construction of a NPP requires a great initial investment and a long period of time until the power plant is ready to operate, so the profit usually does not come until 15-20 years after the plant starts its operation making the investment a big risk for the enterprises, even more with the reluctant public opinion and the changes in the energetic politics.

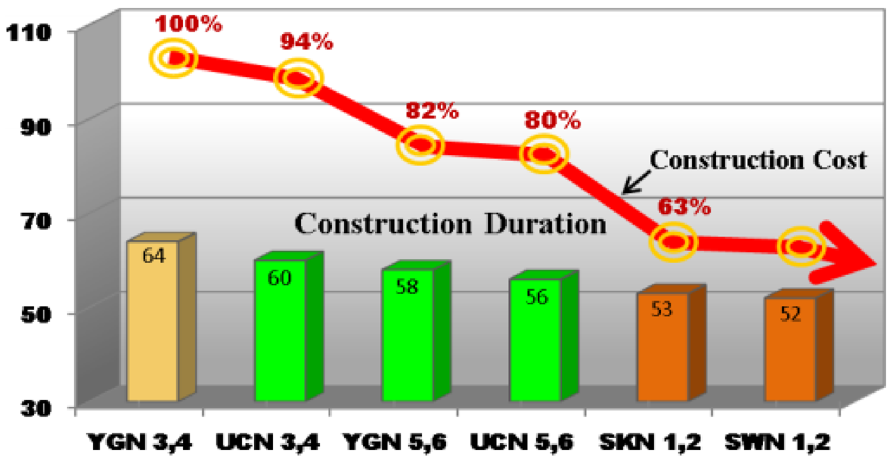

Figure 21: South Korea time and cost reduction with NPP construction increase. Source: IAEA

The relation between the quantity of NPP construction with the time and the cost is direct, as more demand of NPP exist more enterprises specialize and the competition is greater causing a reduction in both cost and time of construction. The figure 21 shows how this effect is applied in a practical situation, specifically South Korea case a country that actually has 24 NPP in operation [17].

As can be observed with the continuous demand the time of construction has been reduced by 12 months and the price is reduced by 40%. This effect has a big impact in the analysis this project is performing as the number of NPP to install is great and so will be the time and cost reduction.

During the past decades a very limited number of NPP has been constructed so the available data sample is very short, however the table 11 shows the prices variation between 1998 and 2009 depending on the region.

Country	Technology	Overnight cost[A]		Investment cost[B]	
		1998	2009	1998	2009
Europe					
Belgium	PWR (EPR)		5 383		7 117
Finland	BWR	2 256		2 672	
France	PWR	1 636		2 280	
	PWR (EPR)		3 860		5 219
Germany	PWR		4 102		5 022
Netherlands	PWR		5 105		6 383
Spain	PWR	2 169		2 957	
Switzerland	PWR		4 043		5 612
East Asia					
Japan	BWR	2 521		3 146	
	ABWR		3 009		3 940
South Korea	PWR	1 637	1 876	2 260	2 340
North America					
Canada	PHWR (Candu)	1 697		2 384	
USA	APWR	1 441	3 382	2 065	4 296
OECD Average		**1 908**	**3 845**	**2 538**	**4 991**

A. Overnight cost includes owner's costs pre-construction and during construction and EPC costs.
B. Overnight cost plus imputed interest charges during construction at 10 percent a year.

Table 11: investment cost per NPP construction in 1998 and 2009.

Source: World nuclear

Looking at the data the lower limit for construction cost will be stablished in the early 1900s price which is slightly lower than the one showed in the table 11 and the average is fixed at 1900 $/kW that will the actual change suppose 1628,53 €/kW which suppose a 38% of the actual investment cost, as the upper limit we will use the investment cost of 2009 as the value has stayed almost constant during the following years being 4991$/kW or 4277,88 €/KW. It is important to note that investment costs are the values to be utilized as will provide a more accurate cost approximation. Relating the investment cost reduction with the time of construction we will obtain a time construction much lower than the 52 moths obtained in Korea, however the process in Korea was highly standardized and the technical necessities of a NPP does not allow to reduce much more the time of construction so the lower limit will be fixed at 48 months or 4 years while the upper limit is fixed at 96 months or 8 years.

- Maximum number of NPP constructions per year

The analysis is being performed worldwide so fixing limits for the maximum number of NPP that are possible to construct at a time is very complex as a global effort in this direction has never been realized but in order to stablish a number the closest possible to the real capacities it is necessary to study the maximum constructions per year during history as figure 22 shows:

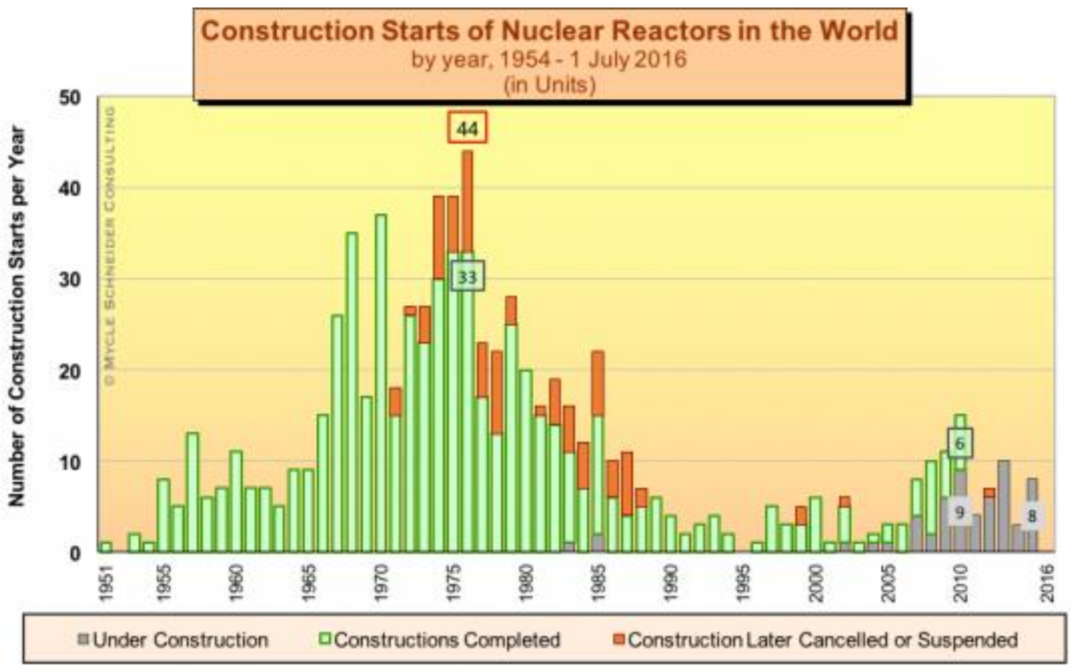

Figure 22: NPP construction starts in history. Source: World nuclear

As can be observed during the 1970s a great number of NPP were constructed even if some of them were cancelled later, the distance in time makes difficult to estimate an accurate number as the technology of construction has greatly developed but also has done the technical and security necessities, anyhow it will be assumed a number of 30 NPP constructions start per year.

- Cost and time reduction along time

In the previous sections we defined lower and upper limits for time and cost as well as the maximum number of construction that can start per year, as this is a theoretical analysis we will assume that all the constructions start at the same time and that the rate of constructions is constant at the maximum, 30 per year. It will also be assumed that the variation in time and cost is equal for all countries and the decrease will be constant. The decrease in both cost at time will occur in periods of 4 years and will meant a reduction of 4 months and 5% of the cost with respect to the initial amount until reaching the lower limit the table below shows the time and cost for each year of the plan.

Year of the plan	Time of construction (months)	Investment cost (€/KW)
1	96	4278
5	92	4064
9	88	3850
13	84	3636
17	80	3422
21	76	3208
25	72	2995
29	68	2781
33	64	2567
37	60	2353
41	56	2139
45	52	1925
49	48	1711
53	48	1629
57	48	1629

Table 12: Time and cost reduction estimation. Source: Own development

- Lifetime of NPP

The design of the old NPP estimated a life time of 25-40 years, however with the introduction of new security systems and the appropriate maintenance this value is been extended for most of the NPP until reaching 60 years. Even if the lifetime is extended the power plants are more secure now than at their beginning of operation due to the introduction of new technologies so this analysis will suppose a 60 years lifetime for its NPP.

- NPP operation cost

In the traditional fuel plants most of the operation cost are related with the cost of the fuel reaching values of 78% for coal fired plants or 87% for gas fired plants but in NPP the cost of the uranium only is 14% of the total operation cost, this value can reach 33% if all the fuel related processes are considered. The table 13 shows the value of uranium as well as the front end processes:

Process	Cost
Uranium	514
Conversion	91
Enrichment	324
Fuel fabrication	256
Total	1185

Table 13: Uranium front end cost. Source: World nuclear

A total cost of 1185 € per kg of uranium is obtained being 3 kg the quantity required to feed a 1 GW NPP, the ones used for this project. Knowing that this cost is only 33% and that each year has 365 days an operation cost of 3,936 million € per year is obtained.

- Health effects of fossil fuels

During the burn of the fossil fuels several gases and particles are emitted, some of them are harmless but others have serious negative effects on human's health. In the process, the air composition is changing the medium conditions for which the humans are adapted reducing the life expectancy or even causing the death. These change in the air and atmosphere conditions have short term and long term effects.

The most known and dangerous long term effect is the global warming which is mainly caused by fossil fuel usage [18], one of the biggest issue the humanity will need to solve in the approaching years, however as the effects of global warming are yet to occur the effect of global warming in human´s health will not be taken into account in this work.

Short term effects have a more direct response in the health and are necessary to analyse. The air pollution caused by fossil fuel burn is considered as the greatest environmental risk to health [18], the WHO stablished a parameter for the air pollution defining the levels dangerous for the human as the table 14 shows but 91% of the world population lives in an ambient that does not fulfil these conditions. In total the ambient air pollution is responsible of 4,2 million premature deaths each year being these deaths concentrated in the countries with a lower level of development and less economical capacities, 91% of the deaths occur in these countries. In addition to the deaths caused by outdoor air pollution another 3 billion people may have health problems as a consequence of the indoor air pollution caused by the pollutants emitted during the cooking if the fuels used are biomass kerosene or coal, these fuels are specially used in the countries that also suffer the greatest impact of outdoor air pollution increasing even more the mortality caused by energy related pollution.

More factors must be considered to define the mortality caused by each fuel as the accidents during construction, mining, accident, operating and another management issues. The table 15 shows the mortality rate caused by each energy source per 1000 TWh:

Pollutant	Maximum permissible concentration (mg/m^3)	
	At any one time	24-hour average
Sulfur dioxide	0.5	0.15
Chlorine	0.1	0.03
Hydrogen sulfide	0.03	0.01
Carbon disulfide	0.5	0.15
Carbon dioxide[a]	6	2
Oxides of nitrogen	0.5	0.15
Non-toxic dusts	0.5	0.15
Soot	0.15	0.05
Phosphorus pentoxide	0.15	0.05
Manganese and compounds	0.03	0.01
Fluorine compounds	0.03	0.01
Sulfuric acid	0.3	0.1
Phenol	0.3	0.1
Arsenic (non-organic compounds, with the exception of arsine)	–	0.003
Lead and compounds (with the exception of lead tetraethyl)	–	0.0007
Metallic mercury	–	0.0003

Table 14: World health organization air quality standards. Source: WHO

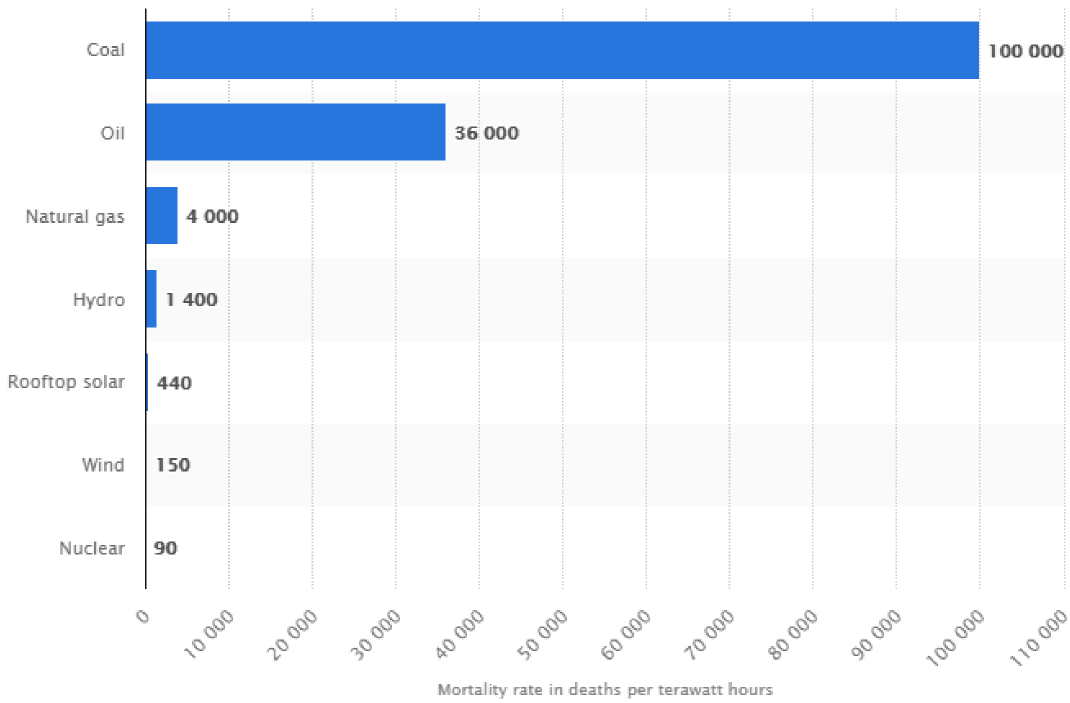

Figure 23: Mortality associated to energy source. Source: Statista

- Human life economic value

There exist several ways to calculate the value of human life, some methods calculate the amount of goods a person is going to be able to generate but in reality, the value is the amount of money that the state is willing to pay for a random citizen in order to avoid his premature death and is a value in continuous increase. As a consequence, the value is very dependent on the country which is estimating it, the countries with a strong economy as United states estimates the value between 7-9 million dollars depending on the source while the value is highly reduced for the poor countries. Another factor that also affect the value is that a life year of a young person is worth a lot more than an elder person´s one. However, in order to simplify calculations, we will assume an average value of human life worldwide at 50000 € [20].

- CO_2 economic value

As previously explained it is complicated to estimate the economic value of reducing the CO_2 emissions focusing in the potential harm it can cause, however there exist a lot of externalities that aim to punish the enterprise that do not fulfil the standards of pollution that vary for each country. This work will use the price of the EU Emissions Trading System which allow the European counties to buy or receive CO_2 emissions in order to avoid economic sanctions. The prices have greatly increased in 2018 reaching an average of 11,9 $\frac{€}{ton\ of\ CO2}$[21]

4.3.2 Oil substitution

In order to analyse the substitution of oil by nuclear fission energy it is necessary to have a more detailed idea about the oil usage and end use.

Oil is responsible of the 33,6% of the total energy produced worldwide, as the total energy produced is 13790 Mtoe the energy produced by oil will be 4633,44 Mtoe.

As the figure 24 shows only the 3,45% of the use of oil can be replaced by fission energy until some other developments are introduced in the energy management. This means that the quantity to substitute is 159,85 Mtoe or 1859 TWh per year.

The change calculated suppose a reduction of 0,147 Gt of equivalent CO_2 per year emissions. To understand the actual impact this reduction will have in total CO_2 emissions we need to compare the result with the total energy related CO_2 emissions which the IEA estimates as 32,53 Gt.

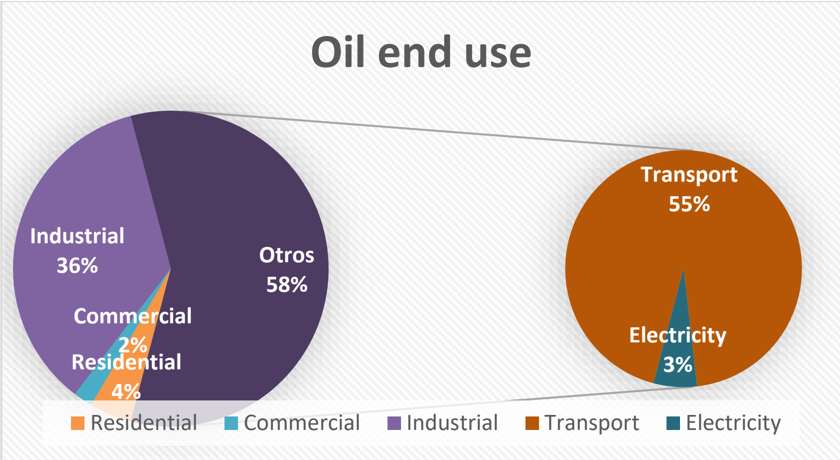

Figure 24: Oil end use. Source: Own development

$$\% \ CO_2 \ reduction \ Oil = \left(\frac{147 \text{ Mt}}{32{,}53 \text{ Gt}}\right) * 100 = 0{,}45 \ \% \tag{22}$$

As can be observed as the amount of CO_2 reduced is huge compared with the total emissions it is a negligible quantity.

For this reduction to be performed the following number of NPP are necessary:

$$Nº \ NPP = \frac{1859 \text{ TWh}}{6728 \text{ GWh}} = 276{,}3 \approx 277 \tag{23}$$

The number is approximated to 277 as it is completely necessary to reach or surpass the energetic necessities to avoid civil and industrial problems.

Now that the number of NPP is defined it is possible to calculate the time and cost of the construction with the data of table 12, the equations (24), (25) and the figure 25:

$$n = \frac{Nº \ NPP}{Nº \ NPP \ per \ year} = 9{,}23 \tag{24}$$

$$Investment \ cost = NPP \ per \ year * \frac{1000}{Life \ time \ NPP} * \left(\sum_{1}^{n_{Oil}} investment \ cost_1 + investment \ cost_n\right) = 19 \ billion \ € \text{ per year} \tag{25}$$

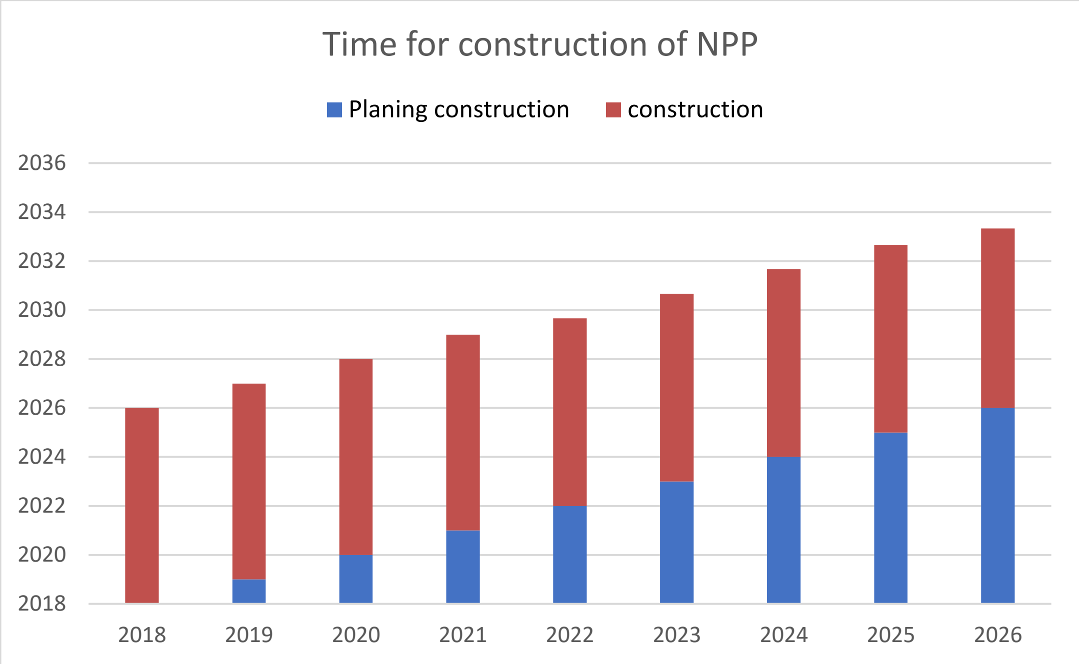

Figure 25: Construction time oil substitution. Source: Own development

The last Nuclear plant will be finished in April of 2033.

As the quantity of CO_2 reduced and the cost of the substitution are known we can calculate the $€/kg\ CO_{2_{\text{reduced}}}$ with equation (26):

$$\frac{€}{kg} CO_{2_{\text{reduced per year}}} = \frac{\frac{Investment\ cost}{NPP\ lifetime} + Nº\ NPP * Operation\ cost}{\text{kg of equivalent } CO_2 \text{ reduced per year}} \tag{26}$$

$$\frac{€}{kg} CO_{2_{\text{reduced per year}}} = \frac{19058 * 10^6 + 277 * 3{,}936 * 10^6}{147 \text{ Mt}} = 0{,}14$$

It is also possible to calculate the premature deaths avoided (PDA) due to the change of energy source applying equation (27) and data from figure 23:

$$deaths\ avoided = \frac{Energy\ substitued\ TWh}{1000} * (deaths_{oil} - deaths_{nuclear})$$
$$= 66760\ deaths\ avoided\ per\ year \tag{27}$$

Once the results of equation 27 are known the cost of each death avoided and the economic value of the deaths avoided can be calculated with equations 28 and 29:

$$\frac{yearly\ cost\ €}{death\ avoided\ per\ year} = \frac{19058 * 10^6 + 277 * 3{,}936 * 10^6}{66760} = 302000 \tag{28}$$

$$Economic\ value_{deaths\ avoided\ per\ year} = 66760 * value\ human\ life \tag{29}$$
$$= 3340\ million\ €$$

The economic value of CO_2 emissions reduced is then calculated with (30):

$$Economic\ value_{CO_2\ emissions\ avoided} = 147\ \text{Mt} * value\ CO2 \\ = 1750\ million\ € \tag{30}$$

The final balance of the substitution and the value which will say if the operation is profitable is calculated in equation (31):

$$Balance\ year = -19058 - 277 * 3{,}936 + 3340 + 1750 = -15\ billion\ € \tag{31}$$

4.3.3 Gas substitution

The same procedure than in oil will be performed, firstly an analysis of the world use of gas allows us to define that gas is responsible of the 22,3% of total energy generation meaning 3075,17 Mtoe.

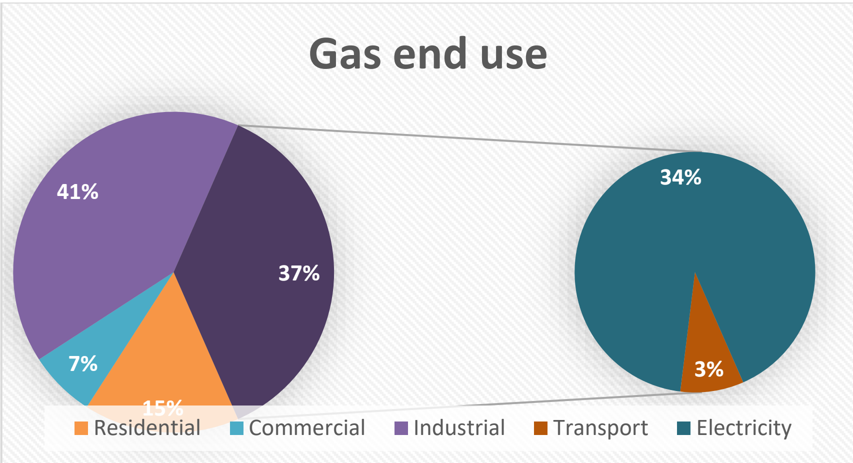

Figure 26: Natural gas end use. Source: Own development

Now the end use of carbon must be analysed in order to do so the data show in figure 25 is necessary.

As can be observed 33,67% of the gas is used for generating electricity implying a great increase in the percentage compared with the 3,45% of oil so the substitution will have a much greater effect and bigger inversion will be needed. The percentage applied to the total energy leads to a result of 1035,41 Mtoe or 12040 TWh per year.

The substitution supposes a reduction of 2,4 Gt of CO_2 equivalent per year.

$$\%\ CO_2\ reduction\ Gas = \left(\frac{2{,}4\ \text{Gt}}{32{,}53\ \text{Gt}}\right) * 100 = 7{,}5\ \% \tag{32}$$

The number of NPP in this case is the following (equation 23):

$$Nº\ NPP = \frac{12040\ \text{TWh}}{6728\ \text{GWh}} = 1789{,}8916 \approx 1790 \tag{33}$$

Now that the number of NPP is calculated we follow the same procedure than in oil with the data of table 12, the equations (34), (35) and the figure 27:

$$n = \frac{Nº\ NPP}{Nº\ NPP\ per\ year} = 59{,}667 \quad (34)$$

$$Investment\ cost\ = NPP\ per\ year * \frac{1000}{Life\ time\ NPP} \quad (35)$$

$$* \sum_{1}^{n} investment\ cost_1 + investment\ cost_n\ = 83300\ billion\ €\ per\ year$$

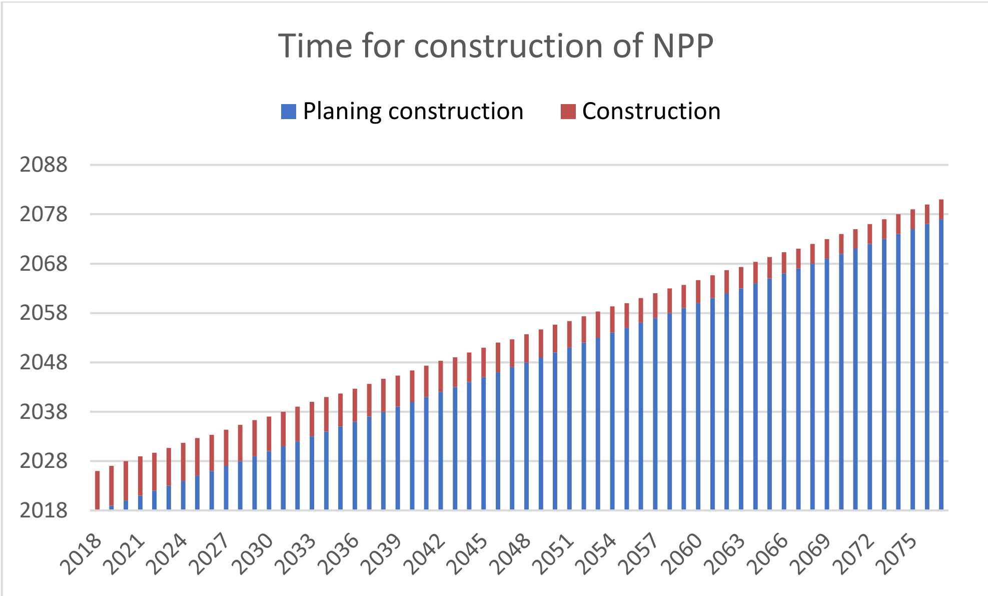

Figure 27: Construction time natural gas substitution. Source: Own development

The last Nuclear plant will be finished in January of 2084.

As the quantity of CO_2 reduced and the cost of the substitution are known we can calculate the $€/kg\ CO_{2_{\text{reduced}}}$ with equation (36):

$$\frac{€}{kg} CO_{2_{\text{reduced}}} = \frac{83300 * 10^6 + 1790 * 3{,}936 * 10^6\ €}{2{,}42763 * 10^{12}\ \text{kg of equivalent}\ CO_2} = 0{,}03721\ \frac{€}{kg} \quad (36)$$

It is also possible to calculate the premature deaths avoided due to the change of energy source applying equation (37) and data from table 12:

$$deaths\ avoided\ per\ year = \frac{Energy\ substitued\ TWh}{1000} * (deaths_{oil} - deaths_{nuclear})$$
$$= 47000\ deaths\ avoided \quad (37)$$

Once the results of equation (37) are known the cost of each death avoided and the economic value of the deaths avoided can be calculated with equation (38) and (39):

$$\frac{yearly\ cost\ €}{death\ avoided} = \frac{83300 * 10^6 + 1790 * 3{,}936 * 10^6\ €}{47000} = 2\frac{million\ €}{death\ avoided} \quad (38)$$

$$Economic\ value_{deaths\ avoided} = 47000 * value\ human\ life = 2350\ million\ € \quad (39)$$

The economic value of CO_2 emissions reduced is then calculated with (40):

$$Economic\ value_{CO_2\ emissions\ avoided} = 2{,}4\ \text{Gt} * value\ CO2 = 28560\ million\ € \quad (40)$$

And the final balance of the substitution is calculated with the following equation (41):

$$Balance\ year = -83300 - 1790 * 3{,}936 + 2350 + 28560 = -59{,}5\ billion\ € \quad (41)$$

4.3.4 Coal substitution

For third time the same procedure will be used following the same steps being the first one the analysis of the participation of coal in the energy mix. The coal is responsible of the 26% of the energy generation, being this percentage 3585,4 Mtoe.

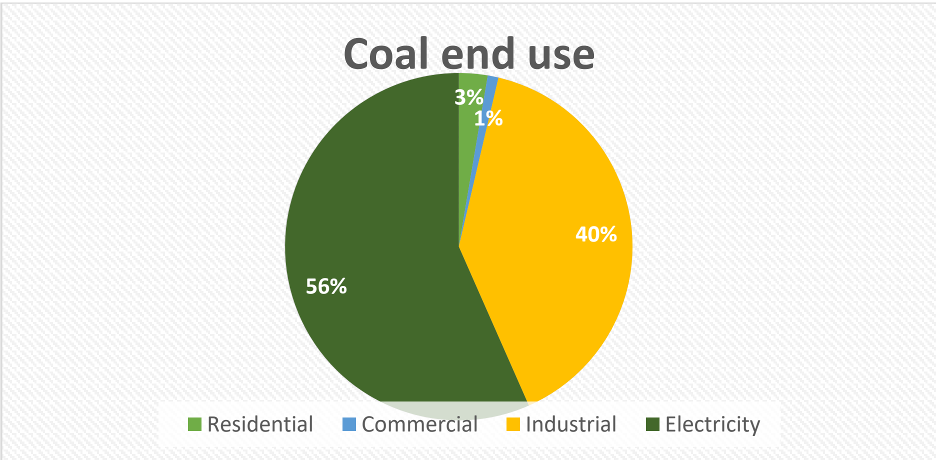

Figure 28: Coal end use. Source: Own development

The end use of the coal will be studied with the data obtained in the figure 28.

The 56% is used for generating electricity being the highest value among the fossil fuels and as the coal is the one with the greater CO_2 generation these change is the most efficient and recommendable. The amount of coal´s energy destined to electricity is 2007,824 Mtoe or 23350 TWh per year.

The fission energy introduction will suppose an 8,3 Gt of CO_2 equivalent emissions reduction per year.

$$\%\ CO_2\ reduction\ Coal = \left(\frac{8{,}3\ \text{Gt}}{32{,}53\ \text{Gt}}\right) * 100 = 25{,}5\ \% \quad (42)$$

The coal´s change will need the following NPP:

$$N^{o}\ NPP = \frac{23350993.1\ \text{GWh}}{6727{,}68\ \text{GWh}} = 3470{,}88344 \approx 3471 \tag{43}$$

Now that the number of NPP is calculated we follow the same procedure than in oil and gas with the data of table 12, the equations (44), (45) and the figure 29:

$$n = \frac{N^{o}\ NPP}{N^{o}\ NPP\ per\ year} = 115{,}7 \tag{44}$$

$$Investment\ cost = NPP\ per\ year \frac{1000}{Life\ time\ NPP} \tag{45}$$

$$* \sum_{1}^{n} investment\ cost_1 + investment\ cost_n \ = 130\ billion\ \text{€ per year}$$

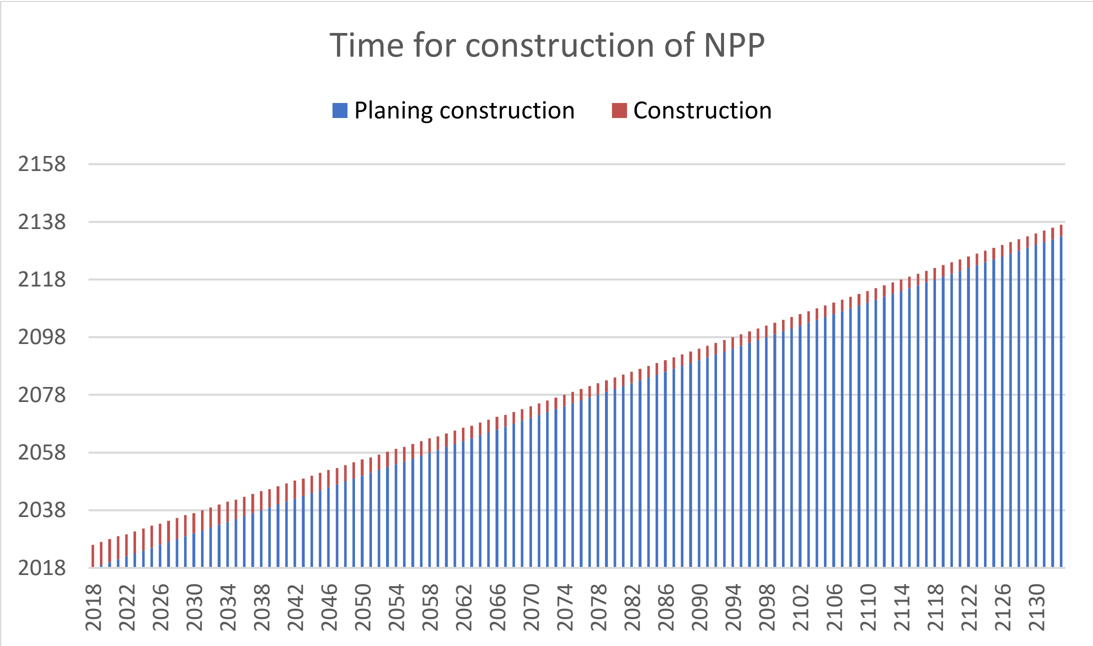

Figure 29: Construction time coal substitution. Source: Own development

The last Nuclear plant will be finished in January of 2140.

As the quantity of CO_2 reduced and the cost of the substitution are known we can calculate the $€/kg\ CO_{2_{\text{reduced}}}$ with equation (46):

$$\frac{€}{kg} CO_{2_{\text{reduced}}} = \frac{130000 * 10^{6}\ + 3471 * 3{,}936 * 10^{6}\ €}{8{,}3\ \text{Gt of equivalent}\ CO_2} = 0{,}017 \frac{€}{kg} \tag{46}$$

It is also possible to calculate the premature deaths avoided due to the change of energy source applying equation (47) and data from figure 23:

$$deaths\ avoided\ per\ year = \frac{Energy\ substitued\ TWh}{1000} * (deaths_{oil} - deaths_{nuclear}) \\ = 2{,}3\ million\ deaths\ avoided \tag{47}$$

Once the results of equation (47) are known the cost of each death avoided and the economic value of the deaths avoided can be calculated with equation (48) and (49):

$$\frac{yearly\ cost\ €}{death\ avoided} = \frac{130000 * 10^6\ + 3471 * 3{,}936 * 10^6\ €}{2{,}3\ * 10^6} = 62000 \frac{€}{death\ avoided} \tag{48}$$

$$Economic\ value_{deaths\ avoided} = 2332997{,}721 * value\ human\ life \\ = 166500\ million\ € \tag{49}$$

The economic value of CO_2 emissions reduced is then calculated with (50):

$$Economic\ value_{\mathrm{CO_2}\ emissions\ avoided} = 8{,}3\ \mathrm{Gt}\ * value\ CO2 \\ = 98770\ million\ € \tag{50}$$

And the final balance of the substitution is calculated with the following equation (51):

$$Balance\ year = -130000 - 3471 * 3{,}936 + 166500 + 28560 = +51{,}4\ billion\ € \tag{51}$$

It is important to note that the lifetime of NPP is only 60 years while the n calculated with equation 24 gives a result of 115,7, this means that the quantity of NPP necessary for the total substitution proposed is impossible at the rate of construction defined for this analysis as the older NPP will finish its activity way before the 3471 NPP number is reached. Making a quick calculation it is possible to verify that the minimum number necessary to fulfil the conditions of the study is the creation of 57,85≈58 NPP a number much higher than the 30 per year stablished and way above the historical maximum created in a year. This rate of construction seems far away from actual possibilities however if the worldwide necessities demand for an immediate solution for the Energetic problem this number may be reached with a huge money investment.

4.3.5 Overview substitution

Fossil fuel substituted	Oil	Natural Gas	Coal
Energy substituted per year (TWh)	1859	12040	23350
Nº NPP necessaries	277	1790	3471
end date starting in January 2018	April 2033	January 2084	Non- reachable Theoretically January 2140
Investment and operation cost per year (million €)	20150	90345	143660
Gt of CO_2reduced per year	0,147	2,4	8,3
Economic value CO_2 reduced (million €)	1750	28560	98770
Premature deaths avoided (PDA) per year	66760	47000	2,3 million
Economic value PDA (million €)	3340	2350	166500
Economic balance year (billion €)	-15	$-59{,}5$	+51,4

Table 15: Overview fossil fuels substitution. Source: Own development

4.3.6 Regulation for new NPP

The regulations regarding the construction and operation of NPP varies depending on the country as each one has its different specification, as the substitution analyzed before is performed at global scale it is impossible to explain all the different regulations. To provide a standard the United States regulation will be explained as it is one of the countries with the highest number of NPP and so the regulation must be well defined and mature.

The responsibility for defining the regulation and providing the licenses is in char of the United States nuclear regulatory commission (U.S.NRC). Applicants to create a new NPP must first follow the requirements demanded for those who want to request a licensee contained in the Code of federal regulations (CFR) [22] being especially relevant the following parts:

26 “Fitness-for-duty programs” [23].

50 “Domestic licensing for product and utilization facilities” [24].

51 “Environmental protection regulations for domestic licensing and related regulatory functions” [25].

52 “Early site permits, standard design certifications and combined licenses for nuclear power plants” [26].

54 “Requirements for renewal of operating licenses for nuclear power plants” [27].

100 “Reactor site criteria” [28].

If the applicant fulfills the conditions the license will be expelled and the construction can begin. Once the NPP is operating the NCR realizes a control of the process in order to inspect, measure and assess the security of the plant and act consequently if the safety conditions are not fulfilled [29].

The NRC also provide ethics rules and guides [30].

Chapter 5: Nuclear fusion

The nuclear fission is the actual alternative to the fossil fuel but it is still dependent on a non-renewable resource so a new alternative is necessary in order have an energy production independent on limited resources and so, a system that can be sustained indefinitely. Also, the risk of nuclear accident makes the fission energy a hazardous option to sustain the majority of the energy mix. Another energy source must surge to solve these problems and one of the possible solutions is the nuclear fusion.

5.1 Fusion in nature

The nuclear fusion is the source of the energy emitted by the sun and the stars, several fusion reactions occurs in the sun generating huge amounts of energy, a little part of these energy is received by the earth and is transformed or accumulated. All the ways of producing energy the human being knows are indirectly or directly produced by the fusion occurring in the sun, the fossil fuels store the energy coming from sun during thousands of years, the wind is produced by the temperatures difference caused by the sun´s energy, the water cycle is caused by those same temperatures differences and the solar energy directly transform the energy coming from fusion into electricity. The fusion process consists in the combination of two light nuclides to form a heavier one, the iron (Fe) is considered the limit of mass to generate energy via fusion, the elements lighter than iron generate energy undergoing fusion while the ones heavier consumes it. The energy is generated due to the mass defect and the Einstein equation $E = mc^2$.

Although several types of fusion reactions occur in the sun 90% of its energy comes from the proton cycle. For this cycle to occur some conditions must be reached, the temperature and the density of the medium used for fusion must be high enough to surpass the Coulomb barrier (equation 16) acting towards the elements. In the stars the temperatures vary between 10-20 million K and densities of 10^{30} particles/m^3 the time average reaction time is around 10^9 years.

The reactions occurring during the proton cycle are the following:

$$2({}_1^1H + {}_1^1H \rightarrow {}_1^2H + e^+ + v_e \qquad 0{,}42\ MeV) \tag{51}$$

$$2({}_1^1H + {}_1^2H \rightarrow {}_2^3H + \gamma \qquad 5{,}49\ MeV) \tag{52}$$

$${}_2^3H + {}_2^3H \rightarrow {}_2^4H + 2{}_1^1H \qquad 12{,}86\ MeV \tag{53}$$

$$2(e^+ + e^- \rightarrow 2\gamma \qquad 1{,}022\ MeV) \tag{54}$$

$$2e^+ + 4{}_1^1H \rightarrow {}_2^4H + 2v_e + 6\gamma \qquad 26{,}7\ MeV \tag{55}$$

In the first reaction two proton or protium (^1_1H) are fused to create deuterium (^2_1H) a positron (e^+) and a neutrino (v_e). Once deuterium has been formed it may fuse with another protium to form Helium-3 (^3_2H) and a high energetic photon (γ).

If the two reactions analysed above occurs twice each one, two nuclei of helium-3 will be formed and fusing them helium and two protium will be formed.

Finally, the positrons generated will be countered by an electron producing more energy. The sun has abundancy of electrons so these reactions occurs naturally.

These reactions are supposed to continue for such a long period of time that it can almost be considered sustainable due to the great amount of hydrogen contained in the sun, approximately 70% of sun mass is hydrogen and the protium is the most abundant hydrogen isotope (about 99% of hydrogen). Also, the probability of success or cross section (σ) of the p-p cycle is low avoidant the sun to increase the temperature and running out of hydrogen faster with the fatal consequences this will have in earth´s life.

5.2 Fusion fuels

In the earth there exist abundant quantities of lighter elements than Fe that could be used to produce energy through fusion process, however, for these elements to react temperature and pressure conditions like sun´s ones are necessary (plasma state) and only a few elements have the possibility to provide an overall energy production positive considering the huge amount of *E* that must be used to reach fusion conditions.

The energy produced by each potential fusion reaction are shown in table 16:

Notation	Reaction	Reaction *E* (MeV)
D-T	$^2_1D + ^3_1T \rightarrow ^4_2He + ^1_0n$	17,58
D-D	$^2_1D + ^2_1D \rightarrow ^3_2He + ^1_0n$	3,27
D-D	$^2_1D + ^2_1D \rightarrow ^3_1T + ^1_1p$	4,032
D-$^3_2$He	$^2_1D + ^4_2He \rightarrow ^3_2He + ^1_1p$	18,3
p-$^{11}_5$B	$^{11}_5B + ^1_1p \rightarrow 3^4_2He$	8,7

Table 16:Energy produced by potential fusion fuel reactions. Source: Own development

To initiate a fusion reaction, it is necessary to surpass Coulomb forces (equation 16), to do so enough energy must be provided in form of heat while the particles remain in a delimited area for at least a specific amount of time. The probability of the particles to interact between them is a very important factor for deciding the most appropriate reaction from table 16. The figure 30 shows the relation between the cross section (σ) and the particle energy showing that the D-T reaction is the more suitable one as the conditions to reach the maximum σ are much accessible that the other ones.

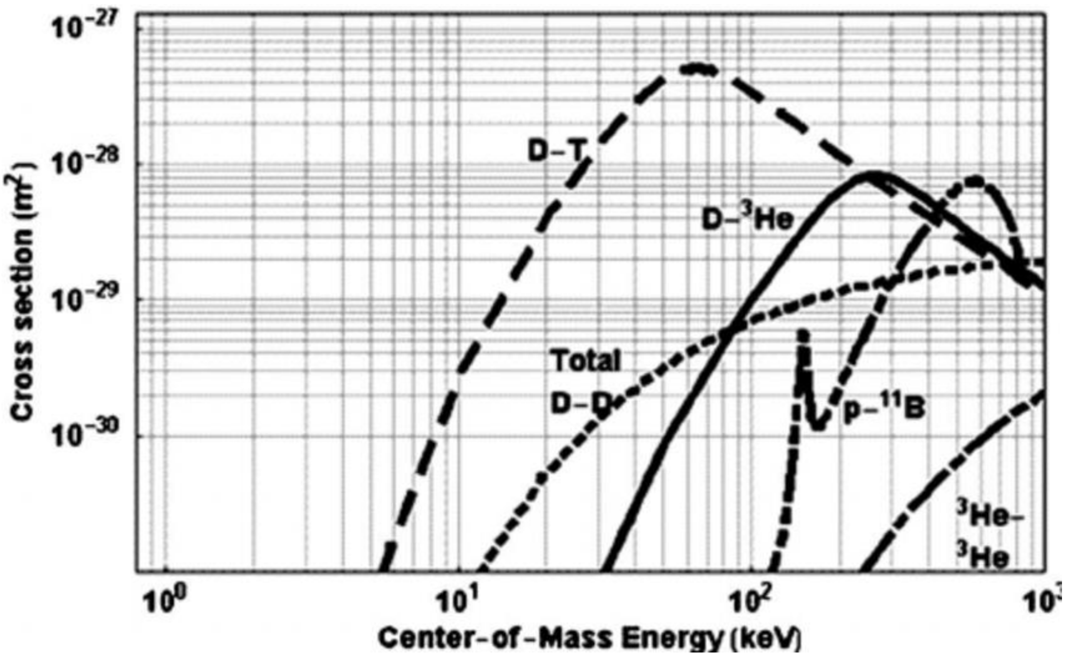

Figure 30: Cross section depending on energy. Source: Researchgate

Due to the Maxwell distribution effect [31] it is not necessary to reach the approximately 90 keV theoretically requested but only 10 keV in an appropriate confinement conditions.

So, the most suitable reaction is the D-T therefore a further explanation of this reaction will be performed.

The deuterium (D) is an abundant element in earth, it is found in water in proportions of 1/50000 [32], so approximately 30 g of D are obtained per 1 m^3 of water and these quantity is increased in heavy water. As the water is so abundant in earth the D may be considered as an almost never-failing resource. The tritium (T) is a more problematic resource as it is not found in nature and therefore must be produced from lithium (Li) composed by 7,5% ${}^{6}_{3}Li$ and 92,5% ${}^{7}_{3}Li$ [33] through neutron capture as equations 56 and 57 show:

$$ {}^{1}_{0}n + {}^{6}_{3}Li \rightarrow {}^{3}_{1}T + {}^{4}_{2}He + 3{,}27\ MeV \tag{56}$$

$$ {}^{1}_{0}n + {}^{7}_{3}Li \rightarrow {}^{3}_{1}T + {}^{4}_{2}He + {}^{1}_{0}n - 2{,}47\ MeV \tag{57}$$

The half-life of T is very short 12,3 years so it is recommendable to produce it at the nuclear plant taking advantage of the neutrons produced during fusion process.

From the 17,58 MeV generated during D-T reaction 14,06 are taken by the neutron while the rest stay with the helium. It is predictable that both D-D reactions occur as a consequence of confinement and plasma physics. Note that one of the D-D reactions generates T that need to be removed.

5.3 Fusion confinement

For a fusion reaction to be economically viable it is necessary to fulfil a relation between temperature (T) time (τ) and plasma density (n), Tτn, at certain level of the three fusion products the reaction becomes self-sustaining, this value is called ignition and is about $5{*}10^{21}m^{-3}s$ KeV [34] for D-T reaction.

- Temperature
  The temperature required is 100* 10^{6} K for both magnetic and inertial confinement, a temperature that is so difficult to reach that three separated heating systems are necessary Ohmic, Neutral beam and Radio-frequency.
- Time
  The helium particles that stay in the plasma collides with the unburn fuel reducing drastically external heat required but time is needed for this effect to occur, usually 1 s is needed in magnetic confinement and $1{*}10^{-9}$s in inertial one.
- Density
  It is necessary to have a high density to force the particles to collide and interact between them while the natural movement of plasma is to spread as much as possible but if too much density is obtained the electrons begin to collide with the neutrons producing bremsstrahlung [35] radiation and preventing fusion from occurring. To create the appropriate density, magnetic fields are generated around the plasma. In magnetic confinement values are around $1{*}\,10^{20}\,m^{3}$ while in inertial are $1{*}10^{30}\,m^{3}$.

5.3.1 Inertial confinement

The inertial confinement tries to produce fusion by comprising 3 mg of D-T into hollow spheres of 1 or 2 mm of radius with three layers (plastic, D-T frozen and D-T gaseous) reaching very high densities and heating it with very potent lasers until the external layer of the sphere reaches the plasma state, this produces an implosion of the D-T fuel. The inner region comprises while the external releases fusion energy, as the density of the nucleus of the sphere increases the kinetic energy of the inner particles is transformed into inner energy causing a sudden increase of heat.

This process aims to generate fusion during very short periods of time of around $1{*}10^{-9}$s but this type of reactors can only operate in pulses and in order to obtain an economically positive process a lot of development is necessary in laser technology.

5.3.2 Magnetic confinement

This type of confinement aims to concentrate and control the plasma ionized gas direction by using magnetic fields avoiding the plasma elements to touch the walls of the chamber. The contact between plasma particles and the walls is avoided because this contact highly reduces the temperature of the first one. It is based in the Lorentz force described in equation 58 being q particle with electrical mass, E electric field, ν particle velocity and B magnetic field:

$$F = q(E + \nu * B) \tag{58}$$

The charged particles with a $\nu\perp$ will interact with B generating a circular movement perpendicular to B forming spirals around the field lines while they are able to move freely in longitudinal direction as showed in figure 31:

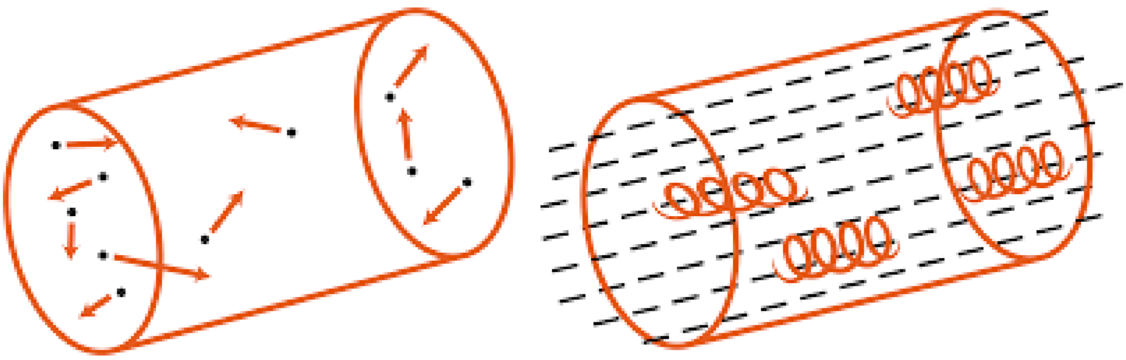

Figure 31: From left to right. Normal charged particles movement. Charged particles movement when interacting with a magnetic field. Source: Standford University

The first one shows the particle movement when no B is interacting, as can be observed the movement is random and therefore the particles will eventually collide with the walls decreasing the plasma temperature and increasing the energetic need for reaching the fusion conditions. The second one shows the movement of particles when a magnetic field is applied to the ionized plasma particles, it can be observed that the particles describe a spiral movement with respect to the B lines allowing some degree of control over its trajectory. With a combination of different magnetic fields, it is possible to control the plasma movement and avoid problematic collisions.

Two different magnetic fields are necessary to avoid the plasma to contact the walls as in linear traps, particles eventually exit at the system end so the fields must be bended to form a torus. Firstly a very strong toroidal magnetic field to stabilize the plasma fluctuations and confining poloidal field generated by the toroidal plasma current. The figure 32 shows all magnetic fields interacting in a tokamak reactor:

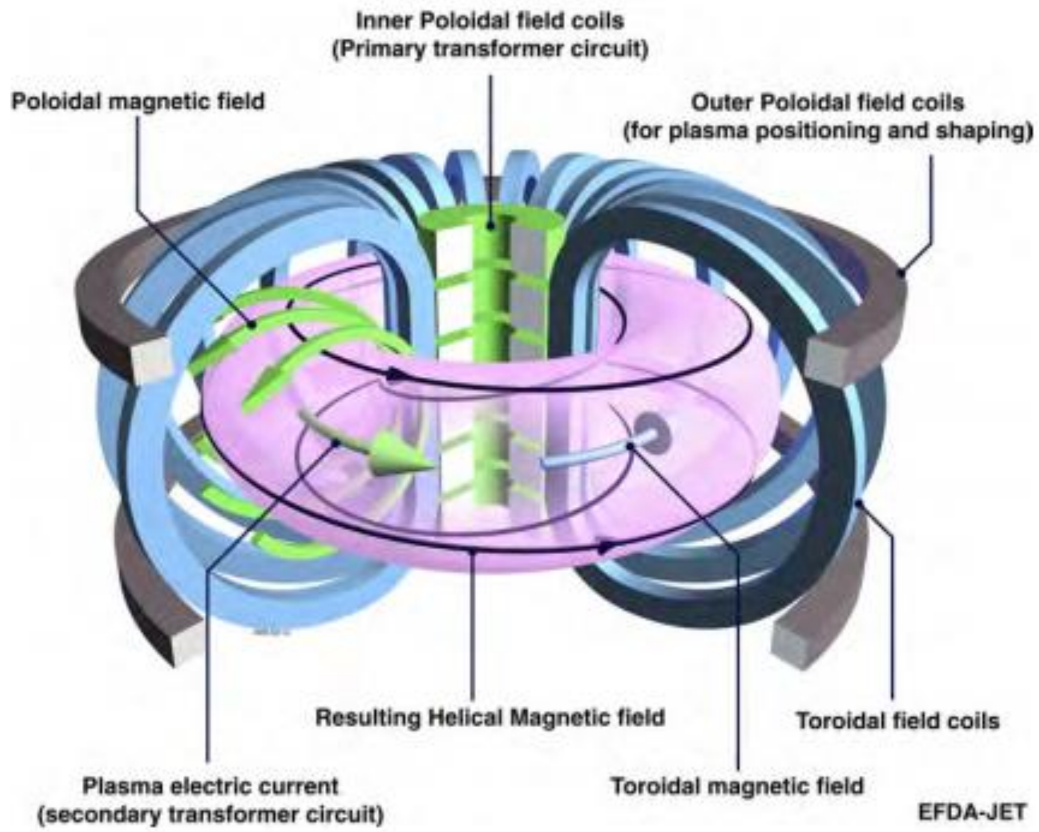

Figure 32: Schematic of Tokamak structure. Source: Madison physics department

Different configurations of magnetic confinement have been developed along history but two of them are specially promising and the investigation is more advanced in them, Tokamak and Stellarator.

- Tokamak
  The Tokamak configuration was firstly proposed in 1951 by Sajarov and Tamm and in actuality is the configuration obtaining the best results mainly because is the one that have more years of investigation behind it. As the figure 51 shows the configuration is symmetric with respect to a central axis with external coils around the chamber walls that generate a very high toroidal magnetic field. Another poloidal magnetic field is necessary to be able to operate the tokamak reactor, this B is generated through inducing an electric current in the plasma in the toroidal direction, the plasma acts as the second transfer circuit. The combination of both circuits results on a helical magnetic field able to contain the plasma. However, to maintain the confinement energy must be introduced periodically to the system, the energy injected will come from the power output reducing the overall efficiency of the system. The main problem of this reactor configuration is that as the conditions approach to the operation ones the current suffers great and extremely fast energy losses that result in the loss of

plasma state making the use of Tokamak configuration for commercial purposes challenging.

- Stellarator

  Stellarator configuration was proposed in 1951 by Lyman Spitzer but due to the complication of its configuration the investigation on it is one generation delayed compared to Tokamak. The figure 32 shows the configuration of an stellarator:

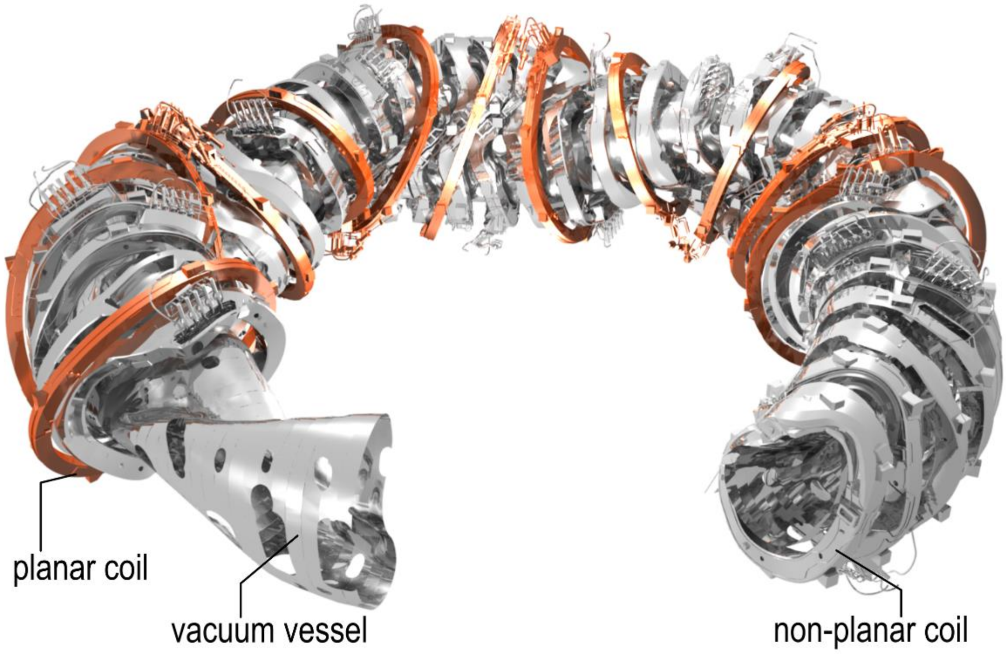

Figure 33: Stellarator structure. Source: Power technology

  As can be observed it is not symmetric and the main difference is that the magnetic fields interaction with the plasma are generated from outside coils exclusively meaning that the plasma does not carry an induced current, the one that complicates the Tokamak operation. This configuration makes the plasma confinement stationary while the current going through external coils keep constant.

5.4 ITER

The ITER is a nuclear fusion reactor under construction in France The ITER is been built with the collaboration of European Union, United States, South Korea, India, Japan, Russia and China. The ITER aims to probe and try all the different variables necessary to operate a fusion reactor at commercial level, to do so fuel ignition (self-sustained) and a sufficiently positive energy balance for making it profitable must be reached. The figure 34 shows the conditions that the ITER aims to reach. It is important to define the factor Q of the plasma shown in equation 59:

$$Q = \frac{Power\ supplied\ by\ reaction}{Power\ of\ auxiliar\ heating} \tag{59}$$

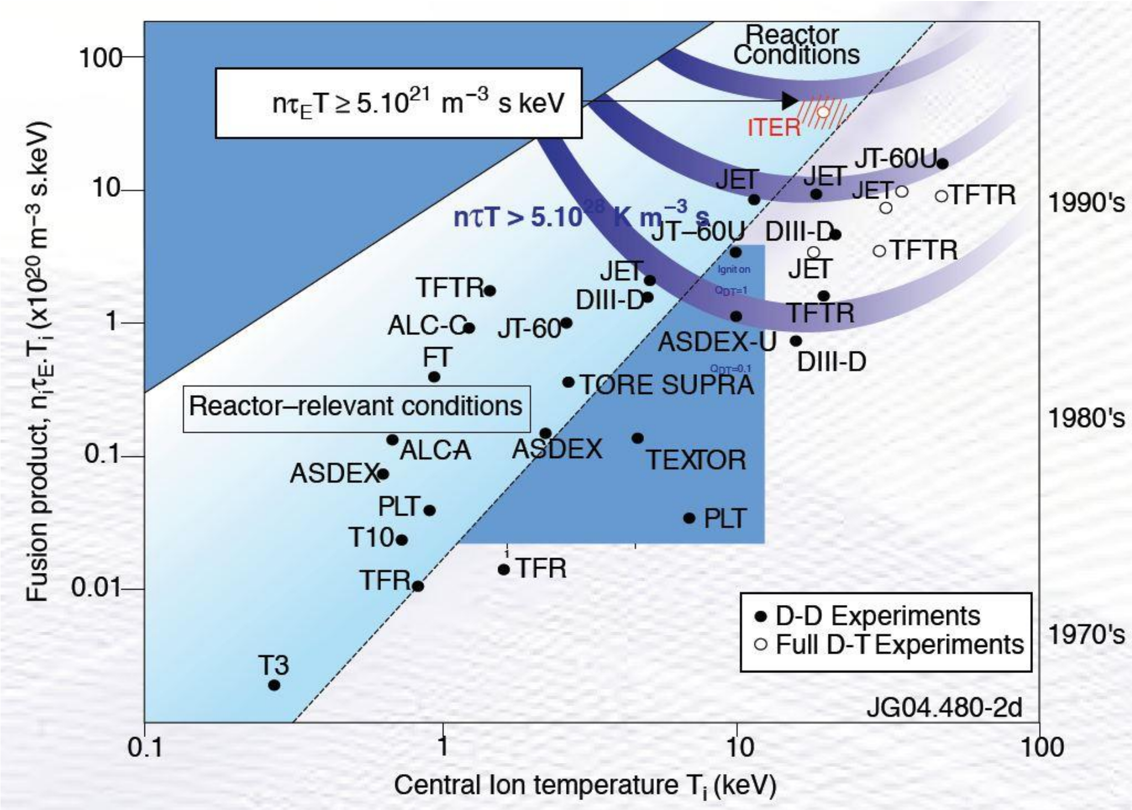

Figure 34: Fusion conditions reached by reactors. Source: Standford University

The ITER official website define another 5 objectives for the ITER project [36]:

1. **Produce 500 MW of fusion power**
   The ITER is designed to have a Q ≥ 10 while the actual record was obtained in the JET and is Q = 0,67. A Q value of 10 means that 500 MW of power will be obtained from 50MW of input heat.

2. **Demonstrate the integrated operation of technologies for a fusion power plant**
   It will be the first plant with the scale that is expected in future commercial fusion reaction so will allow to test the parameters in a more realistic environment that the smaller experimental reactors utilized previously.

3. **Achieve a D-T plasma in which the reaction is sustained through internal heating**
   The ITER dimension and plasma volume make the scientist hope to obtain a relevant increase in both fusion energy and time of sustained reaction.

4. **Test Tritium breeding**
   ITER wants to demonstrate the possibility of producing tritium in the vessel where the fusion is performed using the neutrons produced by it.
5. **Demonstrate the safety characteristics of a fusion device**
   One of the main objectives is to demonstrate that fusion reactors and plasma can be operated without environmental or human consequences.

The ITER´s first D-T plasma is scheduled for 2035.

At the ITER website it is available photos of the actual building state [37] and an interactive worksite tour [38].

Chapter 6: Conclusion

6.1 Technical conclusion

Several signals of a severe upcoming crisis in the energetic sector are foreseen. Energy demand grows every year and is expected to increase 30% between today and 2040. This energetic production is completely dependent on fossil fuels with a **81,7%** of it. However, it´s reserves have been estimated in this project as **206 years** for the **coal** and **310 years** for **natural gas and oil combined**. The scarcity problems of these resources will come much sooner than their estimated end date as the geological location of these reserves will make them inaccessible or simply too expensive to extract. In addition to the limited reserves the negative effects fossil fuels usage has on health and environment are reaching an irreversible point, the fossil fuel burn has a direct effect on **global warming**, the biggest environmental approaching problem that can potentially eliminate human life, and air pollution responsible of **4,2 million premature deaths each year**.

The nuclear fission is the only actual alternative to produce big and constant amounts of energy with no emissions and therefore reducing the health and environmental damage caused by the energetic sector. In this project it was calculated the substitution of the electricity end use share of fossil fuels by fission energy obtaining for **oil** a reduction of **0,147 Gt of CO_2** and **66760 premature deaths avoided per year** with economic balance of **–15 billion € per year**, for **natural gas** a reduction **2,4 Gt of CO_2** and **47000 PDA per year** with economic balance of **–59,5 billion € per year** and finally for **coal** reductions of **8,3 Gt of CO_2** and **2,3 million PDA per year** with economic balance of **+51,4 billion € per year**.

The decision to implement this substitution or not depend on the economic value each government apply to the life of its citizens, for this project a value of 50000 € was applied, and the obligation to choose between two bad options as the reduction in energy demand does not seem realistic, the certainty of the health problems caused by the fossil fuel usage or the latent risk that supposes a nuclear accident that is eventually going to occur, as 0% accident probability does not exist.

It is important to realize that the nuclear fission depends on a limited resource, Uranium, whose economically accessible known reserves are expected to last more than 200 years at the actual rate of consumption, so the nuclear fission implementation is only a measure to win some time until the renewables and other sustainable energies develop. One of the most promising sources of future energy is the nuclear fusion which depends on abundant elements and generates huge amounts of energy from small quantities of fuel while drastically reducing the accident impact and the waste compared to fission. Yet this energy is currently under investigation (ITER) and it is not certain if its commercial use will arrive before the fossil fuels scarcity and its consequences.

6.2 Personal conclusion

From a personal point of view, this project is the end of my academic background in the Energy engineering degree at University Carlos III.

The realization of this project has allowed me to obtain a further knowledge of the energetic sector, especially nuclear, and the future necessities and problems to solve in order to obtain a free of emissions and sustainable energy mix which is the final objective of the energy sector. It was also a great opportunity to apply the knowledge acquired during the degree for a practical problem and a challenge as it is the first time I faced a problem with no solution where I needed to operate with autonomy, no clear references and no certainty that the steps followed were the corrects ones providing me a realistic experience of the work an engineer must develop.

Chapter 7: Time schedule

The project was started in December and delivered at middle June with a duration of 7 and months or 30 weeks. There were no other activities being developed at the same time and implied approximately 450 total hours to complete it (14 hours per week).

The time distribution of the activities is shown in the tables 17 and 18:

Activities time schedule				
	Activity	Starting week	Final week	Duration (weeks)
A	Search for documentation	1	24	24
B	Write Chapter 2.- World Energetic Situation	5	6	2
C	Write Chapter 3.-World fossil fuel reserves calculation	7	12	6
D	Write Chapter 4.-Fossil fuels substitution by nuclear fission	13	19	7
E	Write Chapter 5.-Nuclear Fusion	20	25	6
F	Write Chapter 1.- Introduction	26	26	1
G	Write Chapter 6.- Conclusion	27	27	1
H	Write List of figures Chapter 9.- Bibliography	28	28	1
I	Write Chapter 7.- Time Schedule Chapter 8.- Costs	29	29	1
J	Check project	30	30	1

Table 17: Activities time schedule. Source: Own development

	WEEKS																														
ACTIVITIES		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
	A																														
	B																														
	C																														
	D																														
	E																														
	F																														
	G																														
	H																														
	I																														
	J																														

Table 18: Gantt diagram. Source: Own development

Chapter 8: Costs

The table 19 summarizes the project costs:

<table>
<tr><td>Author</td><td colspan="4">Jorge de Bunes Cansado</td></tr>
<tr><td>Location</td><td colspan="4">UC3M university, Leganes</td></tr>
<tr><th colspan="5">Project</th></tr>
<tr><td>Title</td><td colspan="4">World baseload energy production: Fossil fuels reserves and nuclear energy potential</td></tr>
<tr><td>Duration</td><td colspan="4">30 weeks</td></tr>
<tr><th colspan="5">Costs</th></tr>
<tr><th colspan="5">IVA</th></tr>
<tr><td colspan="5">21%</td></tr>
<tr><th colspan="5">Human resources cost</th></tr>
<tr><td>Category</td><td>Duration (hours)</td><td>Salary (€/h)</td><td>Cost (€) no IVA</td><td>Cost (€) + IVA</td></tr>
<tr><td>Junior engineer</td><td>450</td><td>10</td><td>4500</td><td>5445</td></tr>
<tr><td>Tutor</td><td>25</td><td>100</td><td>250</td><td>302,5</td></tr>
<tr><th colspan="4">Tools cost</th><th></th></tr>
<tr><td>Item</td><td>Price (€)</td><td>Amortization (€)</td><td>Cost (€) no IVA</td><td>Cost (€) + IVA</td></tr>
<tr><td>Computer</td><td>1000</td><td>219,18*</td><td>219,18</td><td>265,2</td></tr>
<tr><th colspan="4">Other cost</th><th></th></tr>
<tr><td colspan="2">Concept</td><td colspan="2">Cost (€) no IVA</td><td>Cost (€) + IVA</td></tr>
<tr><td colspan="2">Electricity</td><td colspan="2">150</td><td>181,5</td></tr>
<tr><td colspan="2">Working space</td><td colspan="2">100</td><td>121</td></tr>
<tr><th colspan="5">Summary</th></tr>
<tr><td>Concept</td><td>Cost (€) no IVA</td><td>Cost (€) + IVA</td><td>Total no IVA</td><td>Total + IVA</td></tr>
<tr><td>Human resources</td><td>4750</td><td>5747,5</td><td rowspan="3">5219,18</td><td rowspan="3">6315,2</td></tr>
<tr><td>Tools</td><td>219,18</td><td>265,2</td></tr>
<tr><td>Other</td><td>250</td><td>302,5</td></tr>
</table>

Table 19: Project overall costs. Source: Own development

* $1000*\frac{400}{5*365\ Useful\ life} = 219{,}18\ €$

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Chapter 10: Acronyms list

Alphabetical order:

BWR	Boiling Water Reactor
CSN	Consejo de Seguridad Nuclear
CDF	Core Damage Frequency
CD	Core Damage
CFR	Code of Federal Regulations
DNA	Deoxyribonucleic Acid
EAF	Energy Availability Factor
EIA	Energy Information Administration U.S.
EF	Emission Factor
ED	Energy Density
EPC	Engineering, Procurement and Construction
HLW	High Level Waste
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
ILW	Intermediate Level Waste
INES	International Nuclear and Radiological Event Scale
ITER	International Thermonuclear Experimental Reactor
JET	Joint European Torus
LET	Linear Energy Transfer
LOCA	Loss of Coolant Accident
LLW	Low Level Waste
NPP	Nuclear Power Plant
NCR	Nuclear Regulatory Commission U.S.
OECD	Organization for Economic Cooperation and Development
PSA	Probabilistic Safety Analysis
PWR	Pressurized Water Reactor
PDA	Premature Deaths Avoided
WHO	World Health Organization

Chapter 11: Symbol list

Appearance order:

Chapter 3:

$I_{Solar\ constant}$	Solar constant irradiance
I_O	Extraterrestial irradiance
N	Day of the year being the first of January n=1
P	Earth point perpendicular to sun plane
δ	Declination angle
φ	Latitude
ω	Hour angle
$H_{Average}$	Average energy reaching earth from sun

Chapter 4:

Δm	Mass defect
Z	Atomic number
A	Mass number
m_p	Proton mass
m_e	Electron mass
m_n	Neutron mass
m_{atoms}	Atom mass
E	Energy
c	Light speed
k	Multiplication factor
F	Force
$k_{constant}$	Coulomb constant
q	Charge
r	Distance between charges
R	Range
E_0	Initial particle energy
QF	Quality factor
H	Dose equivalent

Chapter 5:

${}^1_1H$	Protium
${}^2_1H$ or ${}^2_1D$	Deuterium
${}^3_2H$	Helium
e^+	Positron

ν_e	Neutrino
γ	Energetic photon
e^-	Electron
σ	Cross section
${}_{0}^{1}n$	Neutron
${}_{1}^{3}T$	Tritium
${}_{1}^{1}p$	Proton
${}_{5}^{11}\mathrm{B}$	Boron-11
${}_{3}^{6}Li$	Litio-6
${}_{3}^{7}Li$	Litio-7
T	Temperature
τ	Fusion time
n	Plasma density
F	Force
q	Charge
E	Electric field
ν	Particle velocity
B	Magnetic field
Q	Plasma factor